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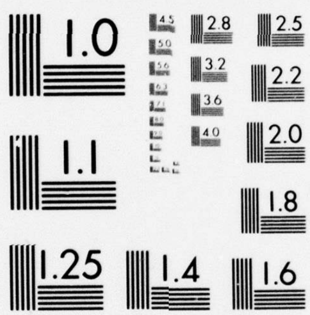
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BOLTED JOINT FATIGUE PROGRAMME

VOLUME IV

STAGE 2 SUPPLEMENTARY INVESTIGATIONS 7 to 9

R H SANDIFER

REPORT OF WORK CONDUCTED UNDER THE DIRECTION OF THE FATIGUE COMMITTEE OF THE ENGINEERING SCIENCES DATA UNIT (PREVIOUSLY THE FATIGUE COMMITTEE OF THE ROYAL AERONAUTICAL SOCIETY)
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BOLTED JOINT FATIGUE PROGRAMME

VOLUME 4

STAGE 2, SUPPLEMENTARY INVESTIGATIONS 7 TO 9

11 May 78

By

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R.H. Sandifer

12 152p.

(Report of work conducted under the direction of the Fatigue Committee of the Engineering Sciences Data Unit (previously the Fatigue Committee of the Royal Aeronautical Society), 251-259 Regent Street, London W1R 7AD).

SUMMARY

The programme consisted of two major parts - a photoelastic investigation into the stress distribution and resulting stress concentration factors in a family of simple bolted joints, and a correlated series of fatigue tests on bolted metal joints having the same geometrical form as the photoelastic ones using a commonly employed aluminium alloy for the plates and a steel in current use for the pins.

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BOLTED JOINT FATIGUE PROGRAMME STAGE 2

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SUPPLEMENTARY INVESTIGATION No.7

THE EFFECT ON ENDURANCE OF RADIUSING THE EDGES OF THE BOLT HOLES, BY PRESS FORMING

1. INTRODUCTION

Supplementary Investigation No.1 showed the beneficial effect on endurance of cold working the inner surface of the bolt hole by forcing an over-size steel ball through the hole - "ballising". An alternative method of increasing the endurance has been proposed, namely to cold work the edges of the bolt hole by using a hard steel tool to press form a radius around the hole edge on both sides of the plate, thus introducing residual compressive stresses into a fatigue critical region. The original set of tools designed for this purpose achieved an increase of endurance, but at the expense of some distortion of the holes, both at the edges and on the inside surface. Two alternative sets of tools were designed subsequently, which reduced the hole distortion but unfortunately **did not** in general lead to the same order of increase of endurance. This report describes the details of the investigation.

The plates and the pins for the specimens were taken from the same stock as that used for the Stage 1 tests, the specimens being prepared by Short Brothers and Harland Ltd, and the fatigue tests carried out by the Department of Metallurgy at Cambridge University, using a 6 Ton Losenhausen machine operating at 1500 c.p.m.

2. NOTATION (Units are in lb and inches throughout)

d	=	Nominal diameter of hole and pin
D	=	Width of parallel section of test specimen
f_t	=	Average Tensile Strength of plate material (from tests)
f_p	=	Average 0.2°/o Proof Stress of plate material (from tests)
K'_t	=	Geometric stress concentration factor based on net area of cross section of test specimen
N	=	Endurance
S_m	=	Mean Stress on net area
S_a	=	Alternating stress on net area associated with S_m
t	=	Thickness of plate specimen

3. TEST PROGRAMME, STRESS LEVELS AND ORIGINAL TOOLS USED FOR PRESS FORMING

The specimens selected from Stage 1 stock for these tests were all of the loaded push fit pin type, medium size and in three groups covering the three values of d/D used in the Stage 1 tests, namely 1/4, 3/8 and 1/2 ($K_t' = 3.73$, 2.72 and 2.22 respectively).

Figure 1 gives details of the specimens.

Testing was carried out at two levels of mean stress, 0.25 f_t and 0.15 f_t. At the higher mean stress four levels of alternating stress were included but at the lower mean stress only two levels of alternating stress were employed. For d/D = 1/2 no tests were made at the lower level of mean stress.

Generally, three nominally identical specimens were tested at each stress level, together with one specimen without pressed formed radii, to serve as a control.

Table 1 presents this original test schedule.

Three press tools were manufactured, one for each diameter of hole corresponding to the three values of d/D and the detail features of these tools were the same except for the diameter - see Figure 2. It will be noted that all the press-tools were designed to have a tapered lead-in of 1.0° to 1.5°, with the last 0.15 in. of length parallel at $d \begin{array}{l} -0.0004 \text{ in} \\ -0.0007 \text{ in} \end{array}$. The radius at the root of the tool was a constant value of ±0.05 in ±0.001 in.

4. ORIGINAL TOOL LOADS

In the interests of uniformity, some preliminary tests were made for each of the three hole diameters, in which the tool was gradually pressed into the hole and records taken at convenient stages, of both the press-tool load and the corresponding gap between the underside of the tool head and the specimen surface. A smear of grease was applied to the tool in order to facilitate ease of removal and care was taken to ensure that the load was applied axially.

The results are presented in Table 2, and from these data it was decided to standardise on a constant tool load for each diameter of hole, each load being that corresponding approximately to a gap of 0.001 in.

These standard tool loads were as follows:

Hole Diameter	d/D	Tool Load (Tons)
5/16 in	1/4	4.0
15/32 in	3/8	4.5
5/8 in	1/2	5.0

5. HOLE DISTORTION DUE TO PRESS-FORMING

As stated in paragraph 3, the specimens were intended to be of the loaded push fit pin type, but when the testing laboratory at Cambridge attempted to assemble them it became clear that relatively large forces would be needed to insert the pins because the holes varied in diameter and concentricity throughout the thickness of the plate. Moreover the majority of the specimens had small lips formed around the edges of the holes, arising from the action of the press-tool. This general hole distortion is shown in Figure 17.

After some consideration it was agreed by all concerned that it would be satisfactory to ream lightly all the holes which were distorted in order to achieve a satisfactory push fit of the pin without causing a significant loss of the residual compression stresses. This action was taken for the majority of the specimens, and thus the loads to insert the pins were kept to the same order as for the corresponding Stage 1 tests.

6. RESULTS OF ORIGINAL TESTS

These are presented in Tables 3, 4 and 5 and plotted on Figures 3, 4 and 5, the numbers 3, 4 and 5 corresponding to the specimen groups with $d/D = 1/4$, 3/8 and 1/2 respectively. In addition to the current control test results, the corresponding Stage 1 test results are also shown, where available.

7. DISCUSSION OF TEST RESULTS USING ORIGINAL TOOLS

At $S_m/f_t = 0.25$

For $d/D = 1/4$ and 3/8 the increase in endurance for the press-formed specimens as compared with the control specimens ranged from a ratio of about 2:1 at high alternating stress ($0.225\ f_t$) to a ratio of about 10:1 at low alternating stress ($0.075\ f_t$ to $0.10\ f_t$).

For $d/D = 1/2$ the increase in endurance was between 5:1 and 10:1 at high alternating stress and between 1:1 and 5:1 at low alternating stress, depending upon whether Stage 1 results or the current controls are used.

It will be noted that, comparing the results of the current controls with the Stage 1 results, there is good agreement between the two at $d/D = 1/4$ but not so good agreement at $d/D = 1/2$.

At $S_m/f_t = 0.15$

At this lower mean stress the increase of endurance was relatively greater than at $S_m/f_t = 0.25$ for both $d/D = 1/4$ and 3/8. There were no tests at $S_m/f_t = 0.15$ for $d/D = 1/2$.

The ratios of increase of endurance for $d/D = 1/4$ range from 2:1 at $S_a = 0.15\ f_t$ to as much as 100:1 at $S_a = 0.10\ f_t$, whereas for $d/D = 3/8$ the endurance increase ratios range from 10:1 at $S_a = 0.15\ f_t$ to 30:1 at $S_a = 0.10\ f_t$. These figures must be regarded as approximate because there was more scatter of results at the lower mean stress than at the higher one.

8. CONCLUSIONS ON ORIGINAL TESTS

To sum up for these tests, there is no doubt that the original design of press-form radius tools did increase significantly the endurances for a given alternating stress over most of the range both for S_m/f_t of 0.25 and 0.15, but there were some attendant disadvantages, namely -

(i) Very high tool loads were necessary in order to close the gap between the tool and the specimen.

(ii) Light reaming of practically all the specimens was essential in order to assemble them to achieve satisfactory push fit standards.

(iii) Small, but inconvenient lips were formed on most of the hole edges, which might prevent satisfactory seating of the joint plates on assembly.

It was decided to examine a selected number of specimens in order to study the nature of the failures. This was done and Table 6 summarises the outcome of these examinations.

9. SUBSEQUENT ACTION

9.1 First Tool Modification

It seemed desirable to attempt to avoid the hole distortion, if possible, and to minimise the growth of the lips, and to this end a revised set of tools was designed and made, - see Figure 6.

The essential differences between the new tools and the original ones were:

(a) a double taper without the parallel portion, instead of the single taper and a short parallel length.

(b) a reduction of root radius from 0.05 in. to 0.02 in.

A pilot programme of tests was planned, covering all three values of d/D but only for a mean stress of $0.25\ f_t$ with three values of alternating stress for each value of d/D. It was thought that if tests at $0.25\ f_t$ were satisfactory, then those at $0.15\ f_t$ would certainly be so. Only one specimen was tested at each stress level. This decision reduced the reliability of any conclusions drawn but was dictated by availability of specimens.

9.1.1 Results of First Tool Modification

(i) Press Tool Loads

As in the original test programme the press tools were advanced steadily into the specimen holes and records taken of the load increments and corresponding gaps between the underside of the tool and the specimen surface. For a given size of hole the records were reasonably uniform. Standardising on a minimum gap of 0.0013 in. the mean press tool loads were:

Hole Diameter	d/D	Tool Load (Tons)
5/16 in	1/4	1.3
15/32 in	3/8	1.9
5/8 in	1/2	2.0

Clearly, these are much less than those required with the original tools, chiefly because of the reduced throat radius of the tools, but consequently there was less material that was cold worked in the fatigue critical region. Also, the lips around the hole edges were reduced slightly and the general hole distortion lessened, thus requiring lower loads to insert the push fit pins.

(ii) Results of Endurance Tests for First Tool Modification

These are given in Table 7 and plotted on Figures 7, 8 and 9 with control and Stage 1 test curves added for comparison.

It appears from a comparison between these figures and those for the original tests that the reduction of the amount of cold working at the hole edges had led to the loss of part or all of previous gains in endurance.

9.2 Second Tool Modification

One more attempt was made to re-design the tool by reverting to the original root radius of 0.05 in, but also creating in the specimen hole a slight interference fit by making the tool diameter to limits of +0.0000 in. to +0.0003 in. This would increase generally the volume of cold worked material. The double taper of the tool was retained. Figure 10 gives details.

Another pilot programme of tests was planned, again for a mean stress of 0.025 f_t but for twice the number of specimens as were tested in the programme for the first tool modification. Half of these were to be tested as manufactured and, assuming that the lips would still arise, the other half were to have the lips removed prior to testing. There was still only one specimen provided for each stress level.

9.2.1 Results of Second Tool Modification

(i) Press Tool Loads

The same procedure was adopted as before, and press tool loads with appropriate gap distances were recorded. A standard minimum gap of 0.003 in. was chosen this time to ensure that the lips would not be damaged. At this minimum gap the standardised tool loads were as follows:

Hole Diameter	d/D	Tool Load (Tons)
5/16 in	1/4	2.1
15/32 in	3/8	3.5
5/8 in	1/2	4.0

These tool loads were intermediate between the original ones and those of the first modified tools. The lips were still formed and were of the order of 0.004 in. in height but not damaged by the press tool. Some reaming of the holes was still required in order to fit the pins to a satisfactory push fit standard.

(ii) Results of Endurance Tests for Second Tool Modification

These are given in Table 8 and plotted on Figures 11, 12 and 13 with control and Stage 1 test curves for comparison.

There was no gain in endurance at $d/D = 1/4$, a little at $d/D = 3/8$ and somewhat more at $d/D = 1/2$, compared with the appropriate controls. Moreover the differences between specimens with and without lips were negligible at $d/D = 1/4$ and $3/8$, but more favourable with lips left on, at $d/D = 1/2$.

9.3 Summary Endurance Curves

Finally, for a better appreciation of the relative merits of all three stages of this investigation, Figures 14, 15 and 16 are presented, dealing with $d/D = 1/4$, $3/8$ and $1/2$ respectively. These show all the endurance curves for a given pin diameter without the detail points plotted.

Only the results for $S_m = 0.25\ f_t$ are included on these figures because of the limited amount of data at $S_m = 0.15\ f_t$, but this data is available and clearly shown on Figures 3, 4 and 5.

10. FINAL CONCLUSIONS

A set of press tools was designed, which created residual compressive stresses in the fatigue critical region of a series of single pin bolted joints, resulting in significantly increased endurances. The increases were greater at the lower values of S_m and of S_a than at the higher values.

However there were some associated disadvantages, namely -

(i) Very high press tool loads were necessary.

(ii) Variation in hole diameter and concentricity throughout the plate thickness occurred, necessitating light reaming before the joint pins could be inserted to a push fit standard.

(iii) Small lips formed around the edges of the holes, affecting adversely the seating of the joint plates on assembly.

Two alternative sets of tools were manufactured varying tool root radius, lead-in design and diameter tolerances of the tool, and further specimens made using these tools. The adverse effects noted above were reduced somewhat but not removed by either of these alternatives. Moreover much, and sometimes all of the increase in endurance achieved when using the original tools was lost.

In the last series of tests half of the specimens had the lips removed before assembly but the resulting endurances were scarcely affected except for the group at $d/D = 1/2$ where the removal caused a significant drop in endurance.

Thus, this method of increasing endurance has proved to be very sensitive to the detail design of the tools and even when the increase is significant it would appear that specimens so made will probably possess to some degree one or more of the three disadvantages noted above. The investigation was therefore discontinued.

SUPPLEMENTARY INVESTIGATION No.7

TABLE 1 SCHEDULE OF ORIGINAL TESTS

All Specimens of "medium" size types 'B' or 'D'

Push Fit Pin - Pin Loaded

Specimen Type	Stress Levels Percentage f_t		Number of Specimens per stress level
	S_m	$\pm S_a$	
2.B.5/16 d/D = 1/4	25	22.5 15 10 7.5	3 with press-formed radius plus 1 without to serve as control
	15	12.5	3 with P.F.R., 1 without
		10	3 with P.F.R., 2 without
2.D.15/32 d/D = 3/8	25	22.5 15 12.5 10	3 with P.F.R., 1 without
	15	12.5 10	3 with P.F.R., 1 without
		7	1 with P.F.R.
2.D.5/8 d/D = 1/2	25	22.5 15 10 7.5	3 with P.F.R., 1 without

P.F.R. = press-formed radius

TABLE 2 PRESS FORMING LOADS - ORIGINAL TOOLS

(a) Specimen Type 2 B 5/16 d/D = 1/4 $K_t' = 3.73$

Specimen Identity	Press Forming Load (Tons)	Tool/Surface Gap (1/1000 in)	Chosen Standard Tool Load for 1/1000 in gap
30.2.D 1st side	1.0 2.0 3.0 3.5 3.6	17 9 5 2 1.5	4.0 Tons
30.2.D 2nd side	1.0 2.0 3.0 3.5 3.6	17 9 5 2 2	
30.2.E	1.0 2.0 3.0 3.2 3.6	18 10 5 4 1	
30.3.C	1.0 2.0 3.0 3.2 3.6	16 9 5 4 1	

Continued

TABLE 2 PRESS FORMING LOADS - ORIGINAL TOOLS

(b) SPECIMEN TYPE 2 D 15/32 d/D = 3/8 $K_t' = 2.72$

Specimen Identity	Press Forming Load (Tons)	Tool/Surface Gap (1/1000 in)	Chosen Standard Tool Load for 1/1000 in gap
12.8.B	1.0	11	4.5 Tons
	2.0	5	
	2.5	2	
	3.0	1.5	
	3.5	0.5	
15.4.B	1.0	16	
	2.0	9.5	
	3.0	7	
	3.5	3	
	4.0	1	
9.20.E	1.0	14	
	2.0	9	
	3.0	5	
	3.5	2	
	4.0	1	

(c) SPECIMEN TYPE 2 D 5/8 d/D = 1/2 $K_t' = 2.22$

Specimen Identity	Press Forming Load (Tons)	Tool/Surface Gap (1/1000 in)	Chosen Standard Tool Load for 1/1000 in gap
15.16.G	1.0	15	5.0 Tons
	2.0	11	
	3.0	7	
	4.0	2	
	4.4	1	
6.11.C	1.0	18	
	2.0	13	
	3.0	9	
	4.0	4	
	4.5	1.5	

SUPPLEMENTARY INVESTIGATION No.7

TABLE 3 RESULTS OF ORIGINAL TESTS - LOADED PUSH FIT PIN Reference Figure 3

SPECIMEN TYPE 2 B 5/16 d/D = 1/4 $K'_t = 3.73$

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
28.2.B 28.2.A* 28.2.D	25	22.5	11 990 11 440 11 170	4.078 4.058 4.046	11 550
28.11.B	25	22.5	5 630	3.750	Control
28.5.A 28.3.A* 28.3.B*	25	15	66 850 35 000 26 990	4.824 4.545 4.430	39 800
28.11.D	25	15	17 470	4.242	Control
28.6.C 28.6.E* 28.6.A	25	10	238 540 165 370 124 500	5.378 5.219 5.095	170 500
28.11.E	25	10	39 950	4.600	Control
28.7.A 28.7.B* 28.7.D	25	7.5	1 471 540 618 370 510 000	6.167 5.790 5.706	773 000
28.12.A	25	7.5	58 320	4.766	Control
28.8.C* 28.8.D 28.8.D	15	12.5	667 260 577 710 427 110	5.823 5.760 5.630	548 000
28.10.C	15	12.5	58 850	4.767	Control
28.8.A 28.8.E 28.9.A	15	10	12 575 560U 10 566 000U 10 487 000U	7.098U 7.022U 7.020U	>11 160 000
28.12.B 28.10.D	15	10	62 770 53 680	4.797 4.730	Control

U denotes unbroken

* Examined for nature of failure

SUPPLEMENTARY INVESTIGATION No. 7

TABLE 4 RESULTS OF ORIGINAL TESTS LOADED PUSH FIT PIN Reference Figure 4

SPECIMEN TYPE 2 D 15/32 d/D = 3/8 $K_t' = 2.72$

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.10.E 12.10.G* 12.10.A	25	22.5	30 750 26 480 19 150	4.487 4.420 4.281	24 900
14.6.D	25	22.5	12 360	4.091	Control
12.11.G 12.11.F 12.11.E*	25	15	78 070 75 910 74 370	4.892 4.880 4.871	76 200
14.6.F	25	15	22 580	4.353	Control
12.12.C 12.12.G* 12.12.F	25	12.5	237 130 165 340 127 010	5.374 5.218 5.102	170 000
14.8.C	25	12.5	23 940	4.378	Control
12.14.C* 12.13.D 12.15.D	25	10	581 150 462 000 332 900	5.764 5.664 5.521	445 000
14.8.E	25	10	74 000	4.869	Control
12.18.A 12.17.D* 12.18.G	15	12.5	12 660 000U 852 320 92 000	7.102U 5.930 4.963	>990 000
14.8.F	15	12.5	66 620	4.823	Control
12.9.B 12.8.B 12.19.B*	15	10	10 133 410U 1 885 000 1 380 000	7.005U 6.275 6.140	>2 970 000
14.5.G	15	10	86 530	4.936	Control
12.19.G	15	7.5	10 314 000U	7.012U	>10 314 000

U denotes unbroken * Examined for nature of failure

TABLE 5 SPECIMEN TYPE 2 D 5/8 d/D = 1/2 $K_t' = 2.22$ Reference Figure 5

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
6.11.C 6.11.D 6.11.E	25	22.5	126 000 115 270 114 080	5.150 5.061 5.056	122 500
6.17.B*	25	22.5	36 290	4.559	Control
6.12.C 6.12.A 6.12.B*	25	15	355 650 176 020 120 290	5.550 5.245 5.080	196 000
6.17.D	25	15	24 880	4.397	Control
6.13.A 6.12.E* 6.12.D	25	10	444 580 324 590 323 090	5.647 5.510 5.509	360 000
6.18.A	25	10	76 060	4.880	Control
6.13.D 6.13.C* 6.13.B	25	7.5	1 488 240 1 036 500 719 380	6.172 6.015 5.856	1 040 000
6.18.B	25	7.5	233 610	5.368	Control

*Examined for nature of failure

SUPPLEMENTARY INVESTIGATION No. 7

TABLE 6 NATURE OF FAILURES OF SOME ORIGINAL SPECIMENS

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Remarks
	S_m	$\pm S_a$		
Specimen Type 2 B 5/16 - d/D = 1/4				
28.2.A	25	22.5	11 440	All specimens had small lips around hole edges and hole diameters varied throughout the thickness (due to press tool distortion). Fatigue cracks occurred on both sides but several specimens fractured completely on one side only.
28.3.A	25	15	35 000	
28.3.B	25	15	26 990	
28.6.E	25	10	165 370	
28.7.B	25	7.5	618 370	
28.8.C	15	12.5	667 260	
Specimen Type 2 D 15/32 - d/D = 3/8				
12.10.G	25	22.5	26 480	Hole distortion similar to specimens at d/D=1/4 but less severe. Fatigue cracks generally on both sides of hole.
12.11.E	25	15	74 370	
12.12.G	25	12.5	165 340	
12.14.C	25	10	581 150	
12.17.D	15	12.5	852 320	
12.19.B	15	10	1 380 000	
Specimen Type 2 D 5/8 - d/D = 1/2				
6.17.B	25	22.5	36 290	Still some hole distortion and formation of lips. All specimens had fatigue cracks on both sides of hole and all specimens failed completely on one side only.
6.12.B	25	15	120 290	
6.12.E	25	10	324 590	
6.13.C	25	7.5	1 036 500	

TABLE 7 RESULTS OF TESTS AFTER FIRST TOOL MODIFICATION Reference Figures 7, 8 and 9

Specimen Type	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
		S_m	$\pm S_a$		
2 B 5/16	29.9.C	25	22.5	8 040	3.905
	29.11.C		15	18 150	4.258
	29.16.C		7.5	126 200	5.100
2 D 15/32	14.14.A	25	22.5	20 890	4.320
	14.15.A		15	78 340	4.893
	14.19.B		7.5	182 550	5.260
2 D 5/8	16.5.D	25	22.5	40 110	4.603
	16.13.E		15	136 280	5.135
	16.12.F		7.5	848 340	5.927

SUPPLEMENTARY INVESTIGATION No. 7

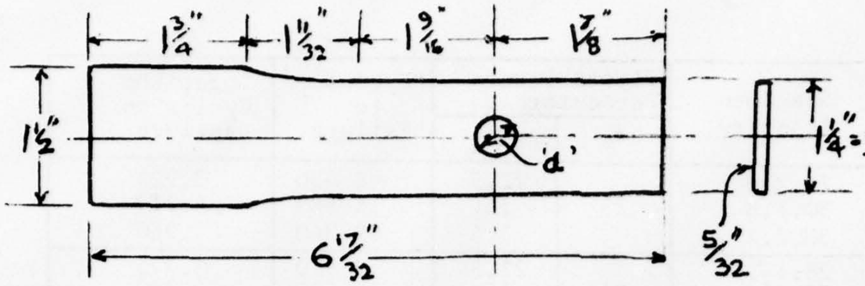
TABLE 8 RESULTS OF TESTS AFTER SECOND TOOL MODIFICATION Reference Figures 11, 12 and 13

Specimen Type	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
		S_m	$\pm S_a$		
2 B 5/16 lipped	29.2.C	25	22.5	8 430	3.925
	30.1.B		15	16 880	4.217
	30.2.A		7.5	89 340	4.950
2 B 5/16 lip removed	28.17.C	25	22.5	5 970	3.775
	29.2.A		15	16 590	4.220
	29.7.A		7.5	81 600	4.911
2 D 15/32 lipped	14.15.B	25	22.5	23 770	4.375
	14.16.D		15	43 030	4.635
	14.17.A		7.5	190 170	5.280
2 D 15/32 lip removed	14.13.A	25	22.5	22 460	4.350
	14.14.B		15	40 410	4.606
	14.16.C		7.5	204 800	5.310
2 D 5/8 lipped	16.2.C	25	22.5	33 060	4.520
	16.3.B		15	244 280	5.388
	16.4.C		7.5	2 882 200	6.460
2 D 5/8 lip removed	15.19.F	25	22.5	38 570	4.586
	16.1.F		15	106 070	5.025
	16.1.G		7.5	935 620	5.970

S.I. No 7 PRESS FORMED RADII

FIGURE 1 DETAILS OF SPECIMENS – 'MEDIUM' SIZE

PLATES Aluminium Alloy to Specification B.S. L71

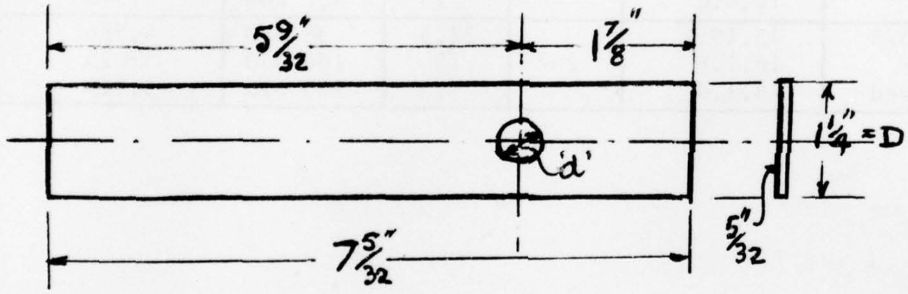


TYPE 'B'
Half Size

Hole Dias. 'd'

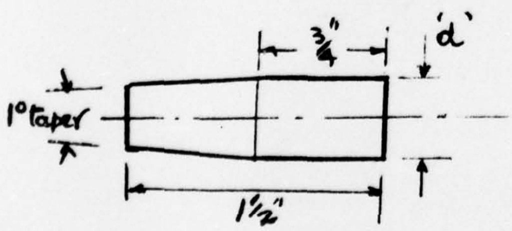
Type 'B' – 5/16"

Type 'D' – 15/32" and 5/8"



TYPE 'D'
Half Size

PINS Steel to Specification B.S. S94



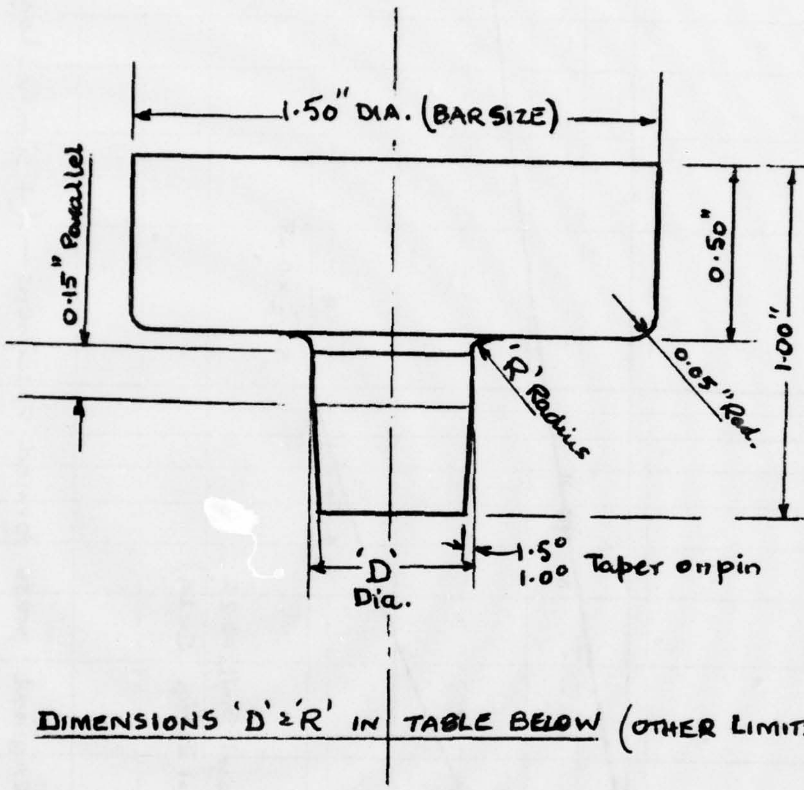
Limits Holes – d ± 0.0003"

Pins – d ± 0.0001"

Selective Assembly to give Push Fit to ± 0.0003"

S.I. No 7 PRESS FORMED RADII

FIGURE 2 ORIGINAL TOOLS



SCALE 2:1

DIMENSIONS 'D' & 'R' IN TABLE BELOW (OTHER LIMITS $^{+0.01}_{-0.00}$)

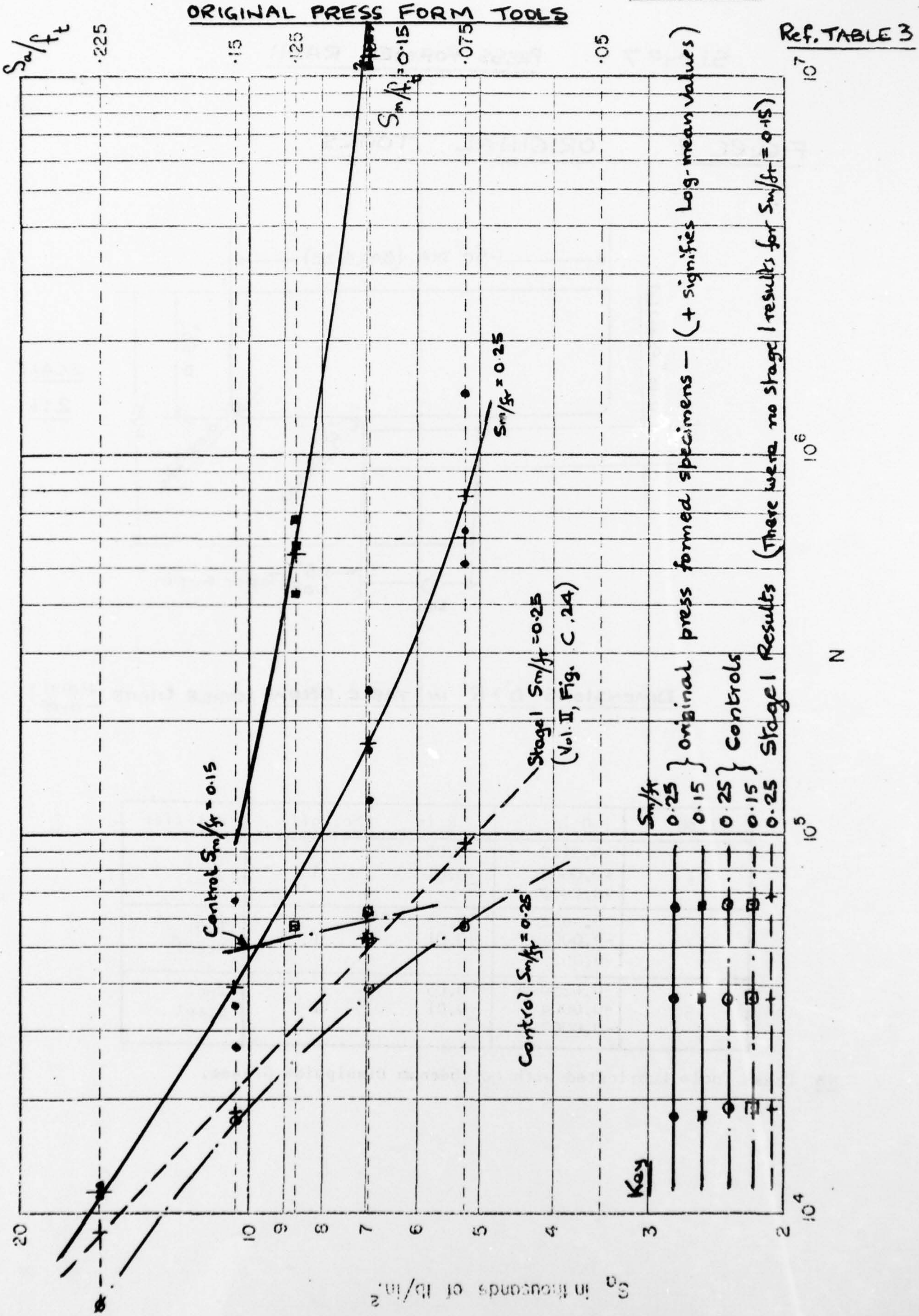
ITEM	D in	R in	No. off	Material
1	0.3125 -0.0004 -0.0007	0.05 ±0.01	1	Tool Steel
2	0.4687 -0.0004 -0.007	0.05 ±0.01	1	Tool Steel
3	0.6250 -0.0004 -0.0007	0.05 ±0.01	1	Tool Steel

NB Press Tools Lubricated with Molybdenum Disulphide Grease.

FIGURE 3 SPECIMENS TYPE 2B 5/16 PUSH FIT PIN PIN LOADED $d/D = 1/4$

ORIGINAL PRESS FORM TOOLS

Ref. TABLE 3

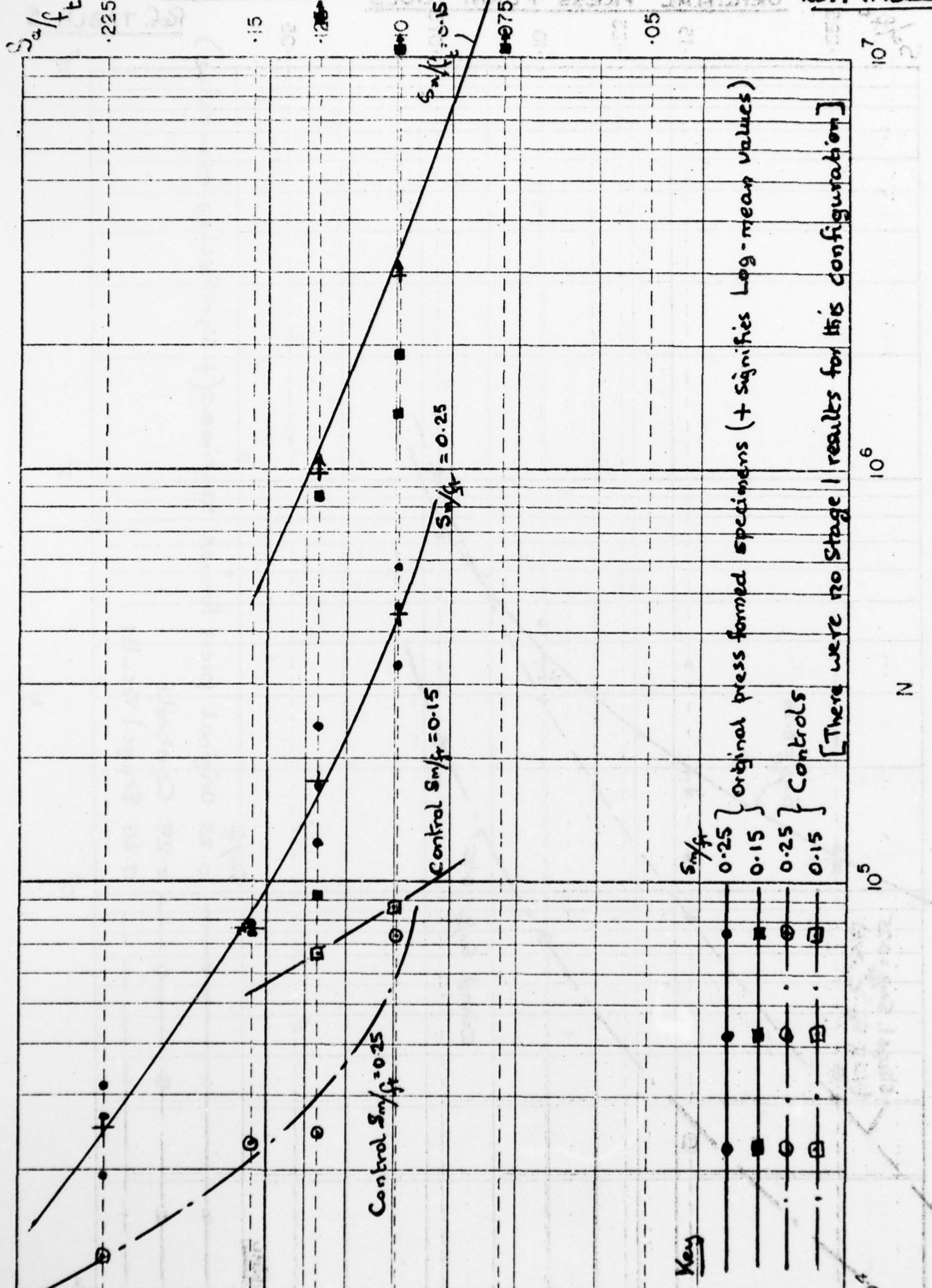


D.I. N° 0

FIGURE 4 SPECIMENS TYPE 2D15/32 PUSH FIT PIN PIN LOADED $d/D = \frac{3}{8}$

ORIGINAL PRESS FORM TOOLS

Ref. TABLE 4



S.I. No 7

FIGURE 5 SPECIMENS TYPE 2D 5/8 PUSH FIT PIN PIN LOADED $d/D = 1/2$

ORIGINAL PRESS FORM TOOLS

Ref. TABLE 5

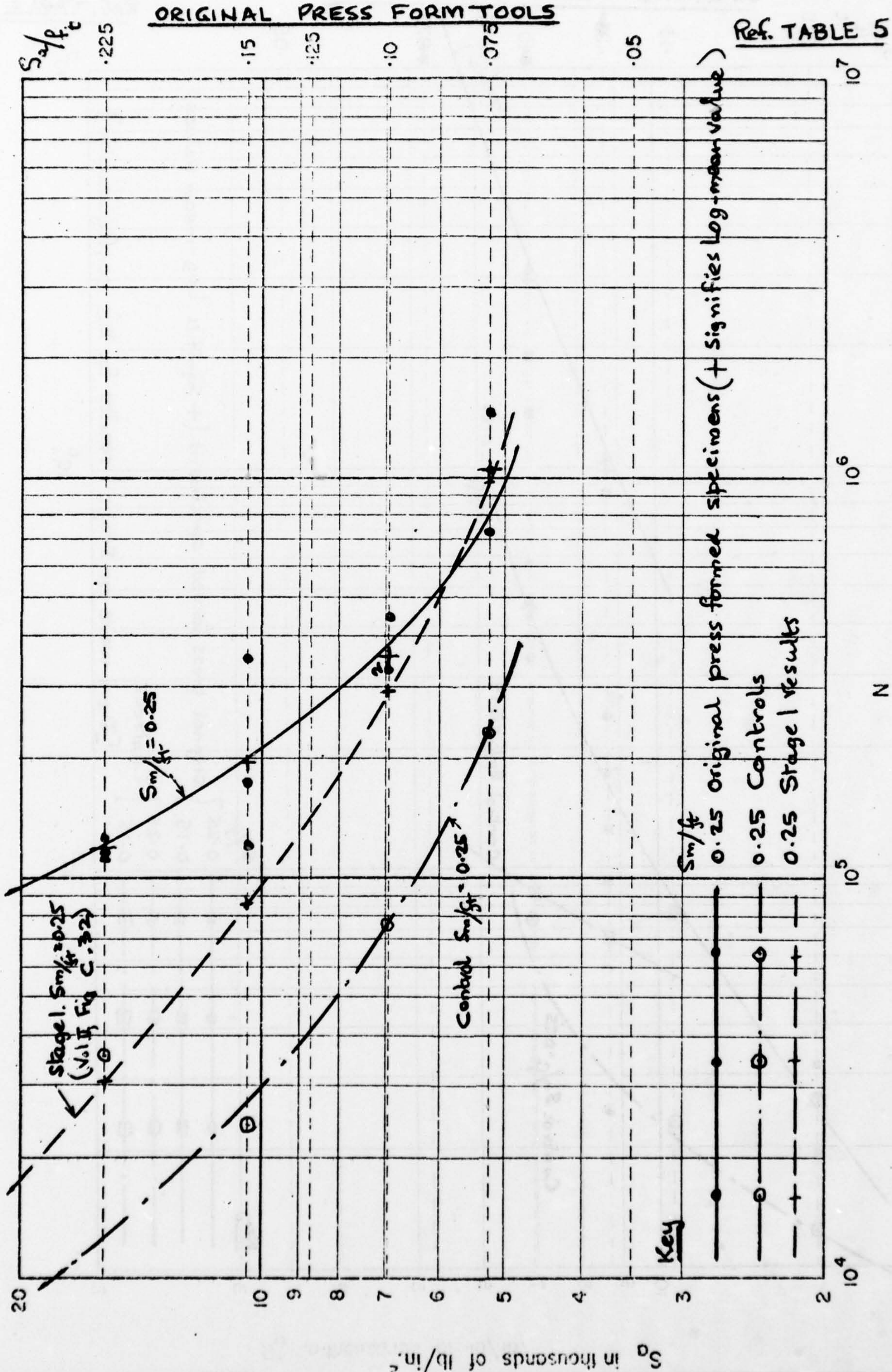
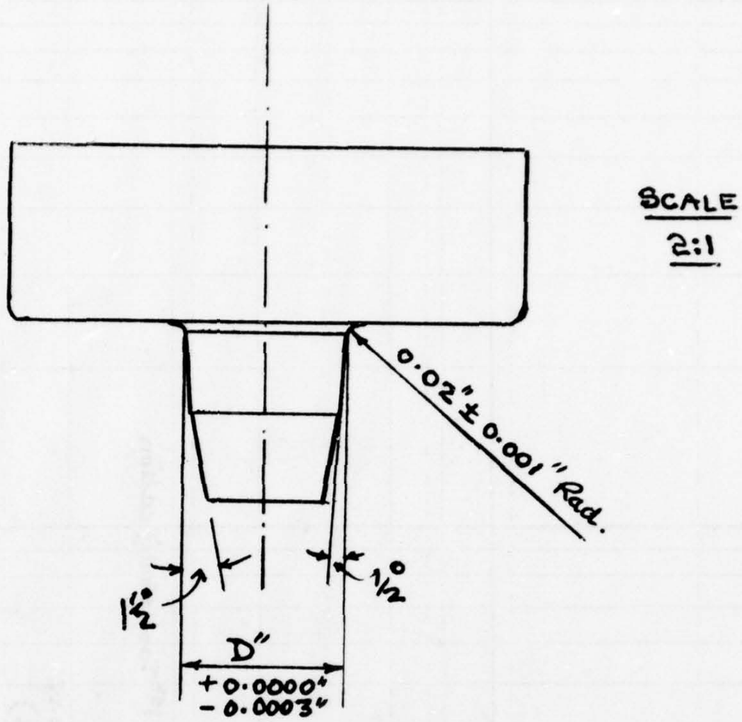


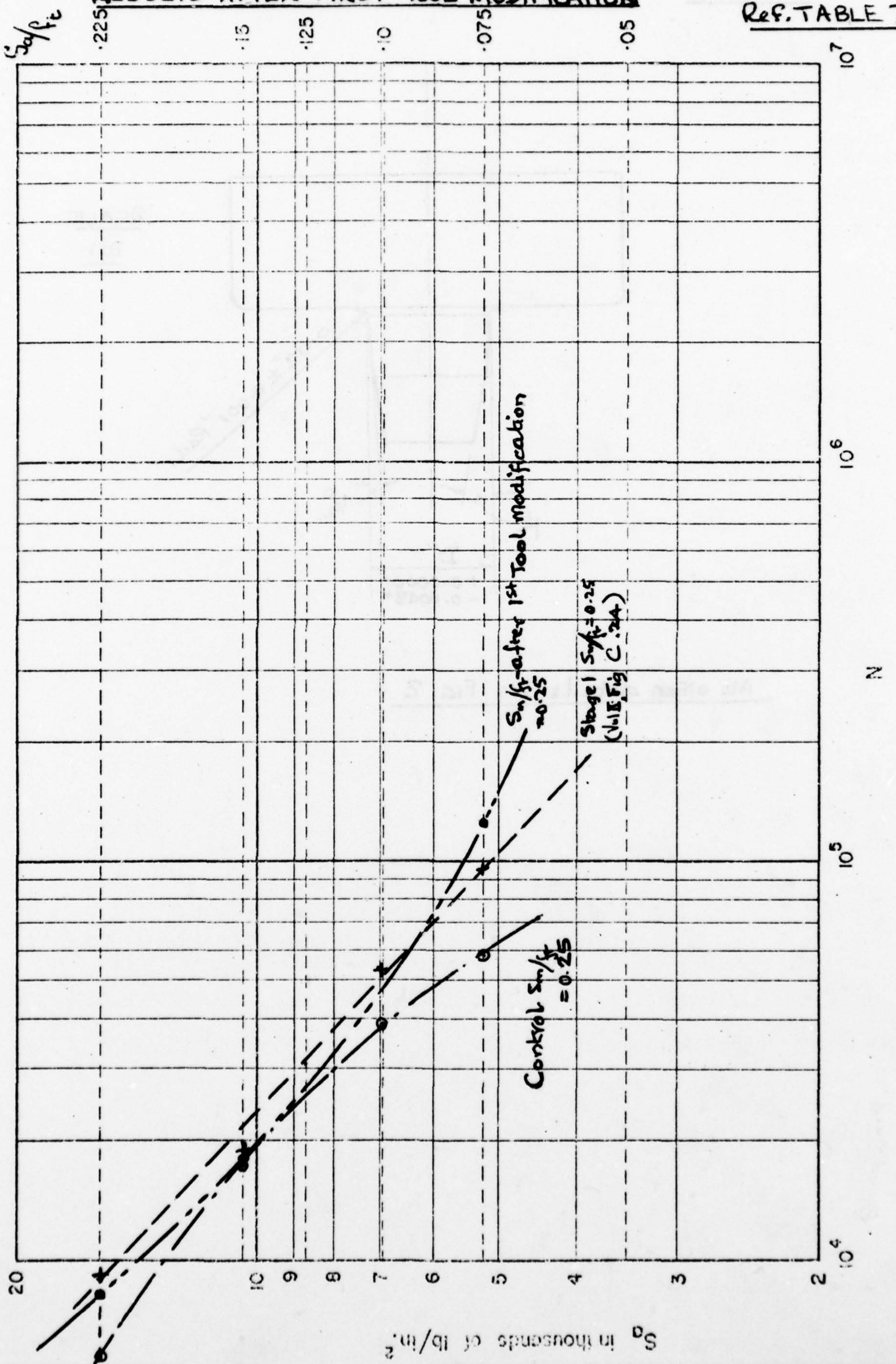
FIGURE 6 FIRST MODIFIED TOOLS



All other details as FIG. 2

FIGURE 7 SPECIMENS TYPE 2B 5/16 PUSH FIT PIN PIN LOADED $d/D = 1/4$

RESULTS AFTER FIRST TOOL MODIFICATION Ref. TABLE 7

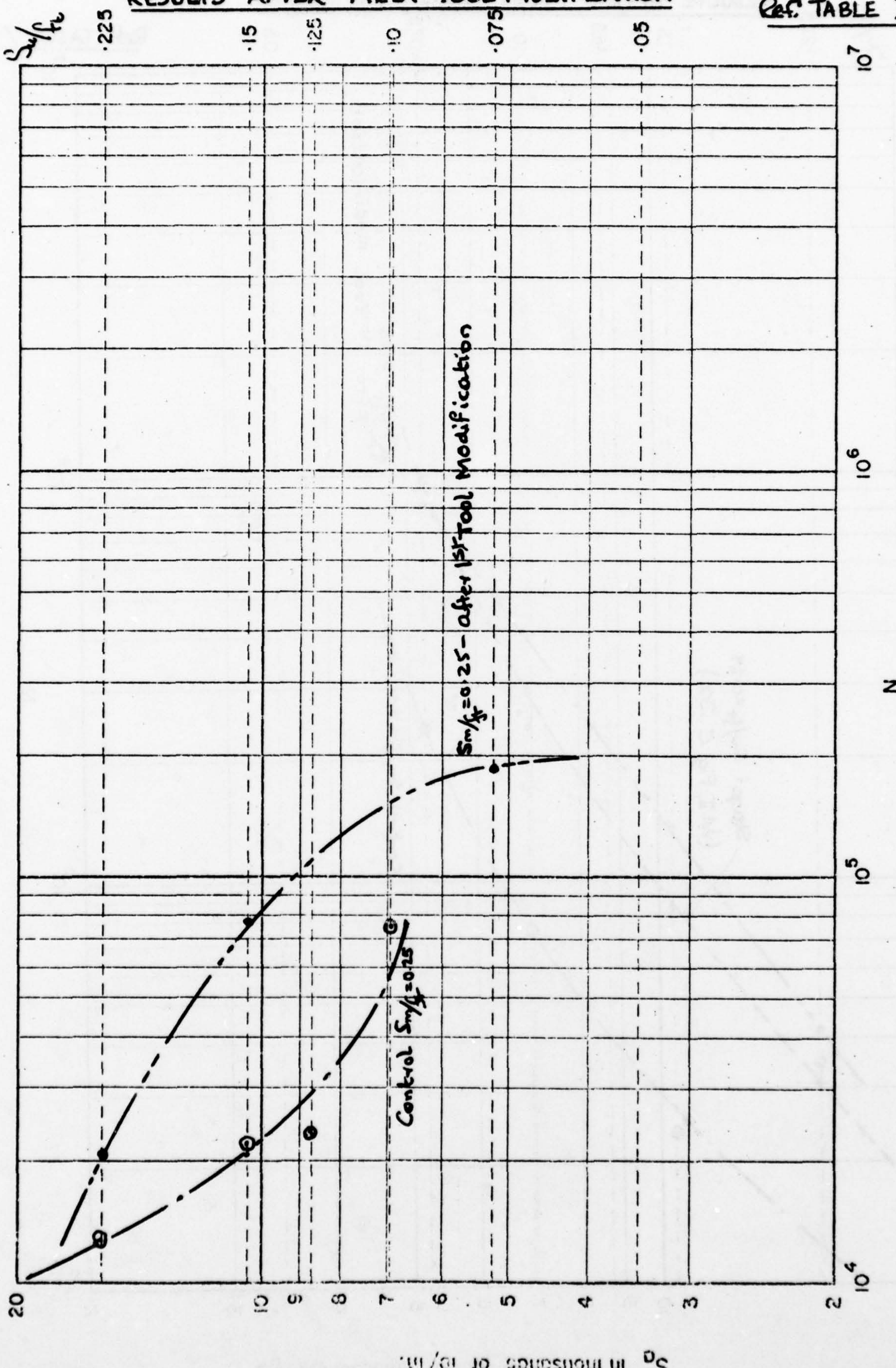


S.I. No. 7

FIGURE 8. SPECIMENS TYPE 2D 15/32 PUSH FIT PIN PIN LOADED $d/D = 3/8$

RESULTS AFTER FIRST TOOL MODIFICATION

REF. TABLE 7



S.I. No. 7

FIGURE 9 SPECIMENS TYPE 2D5/8 PUSH FIT PIN PIN LOADED $d/D = 1/2$

RESULTS AFTER FIRST TOOL MODIFICATION

Ref. TABLE 7

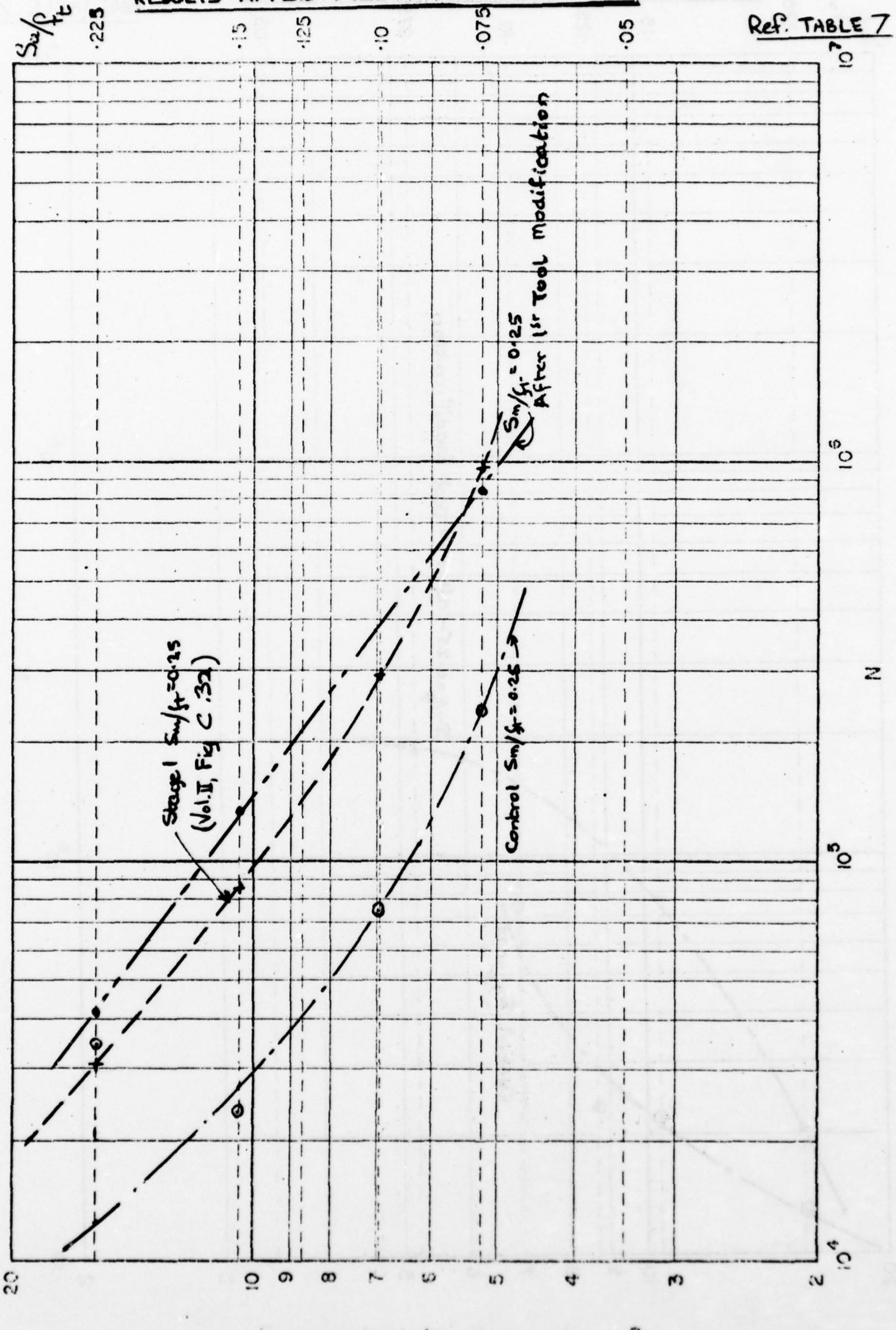
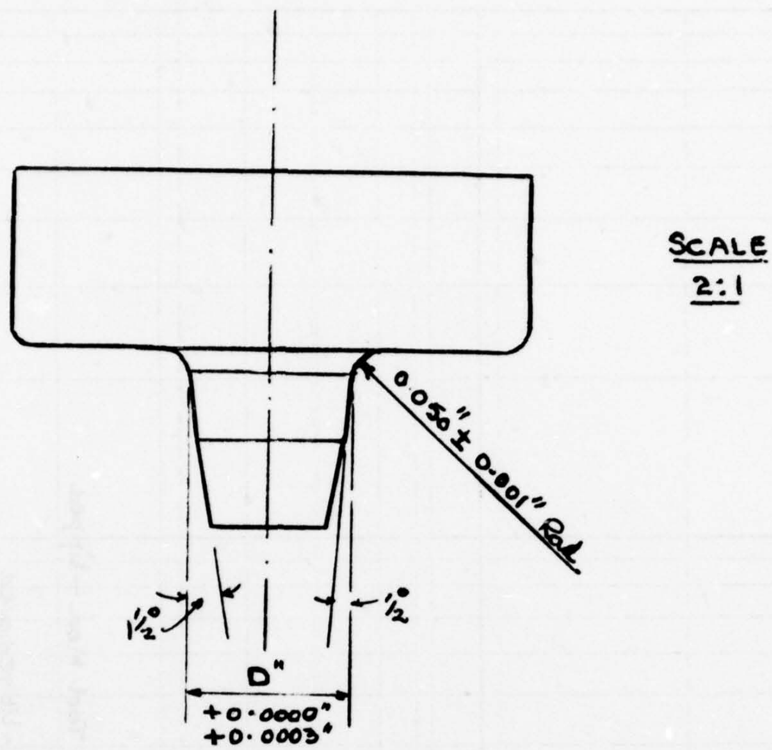


FIGURE 10 SECOND MODIFIED TOOLS



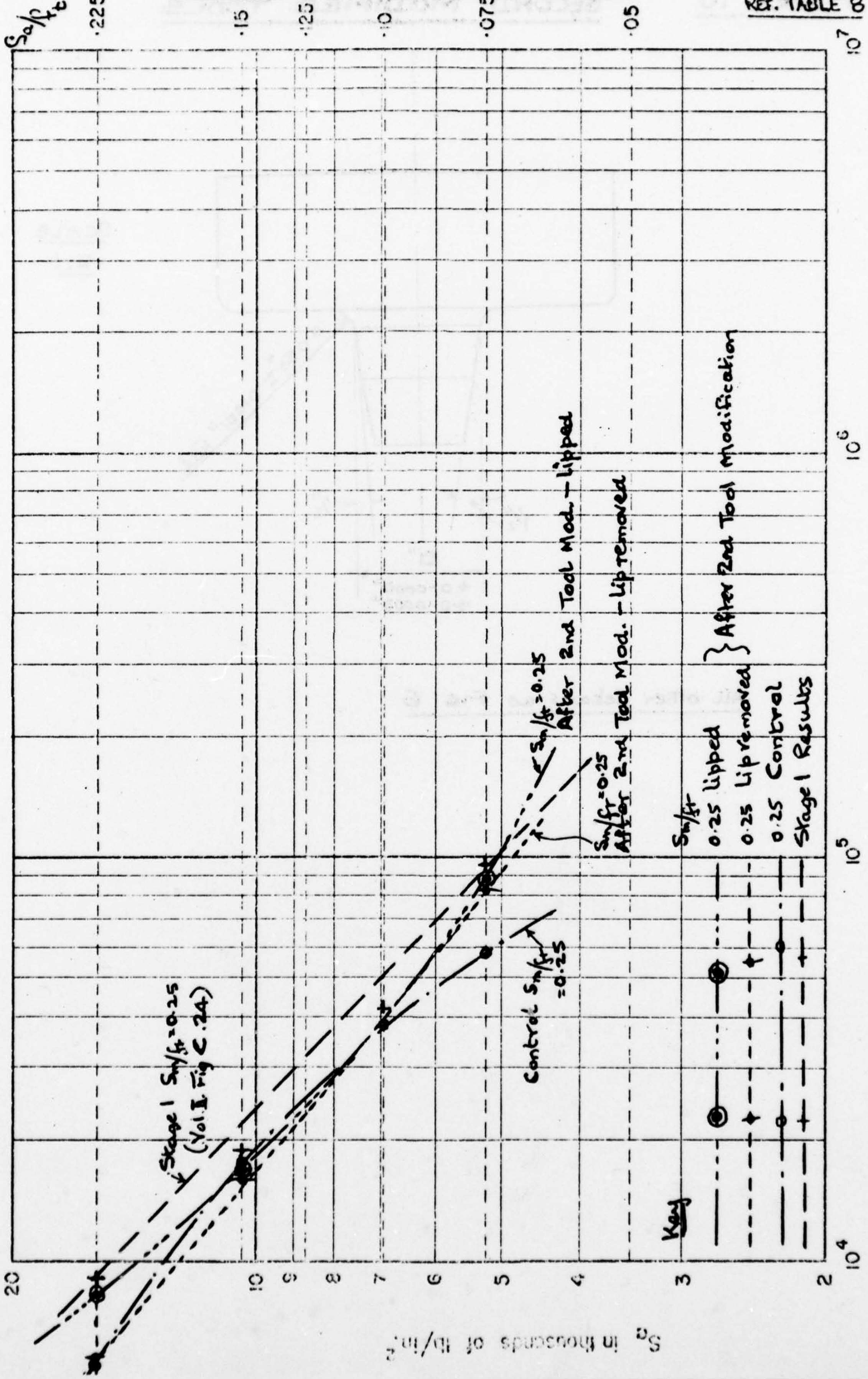
All other details as FIG. 6

S.I. No 7

FIGURE 11 SPECIMENS TYPE 2B 5/16 PUSH FIT PIN PIN LOADED $d/D = 1/4$

RESULTS AFTER SECOND TOOL MODIFICATION

REF. TABLE 8

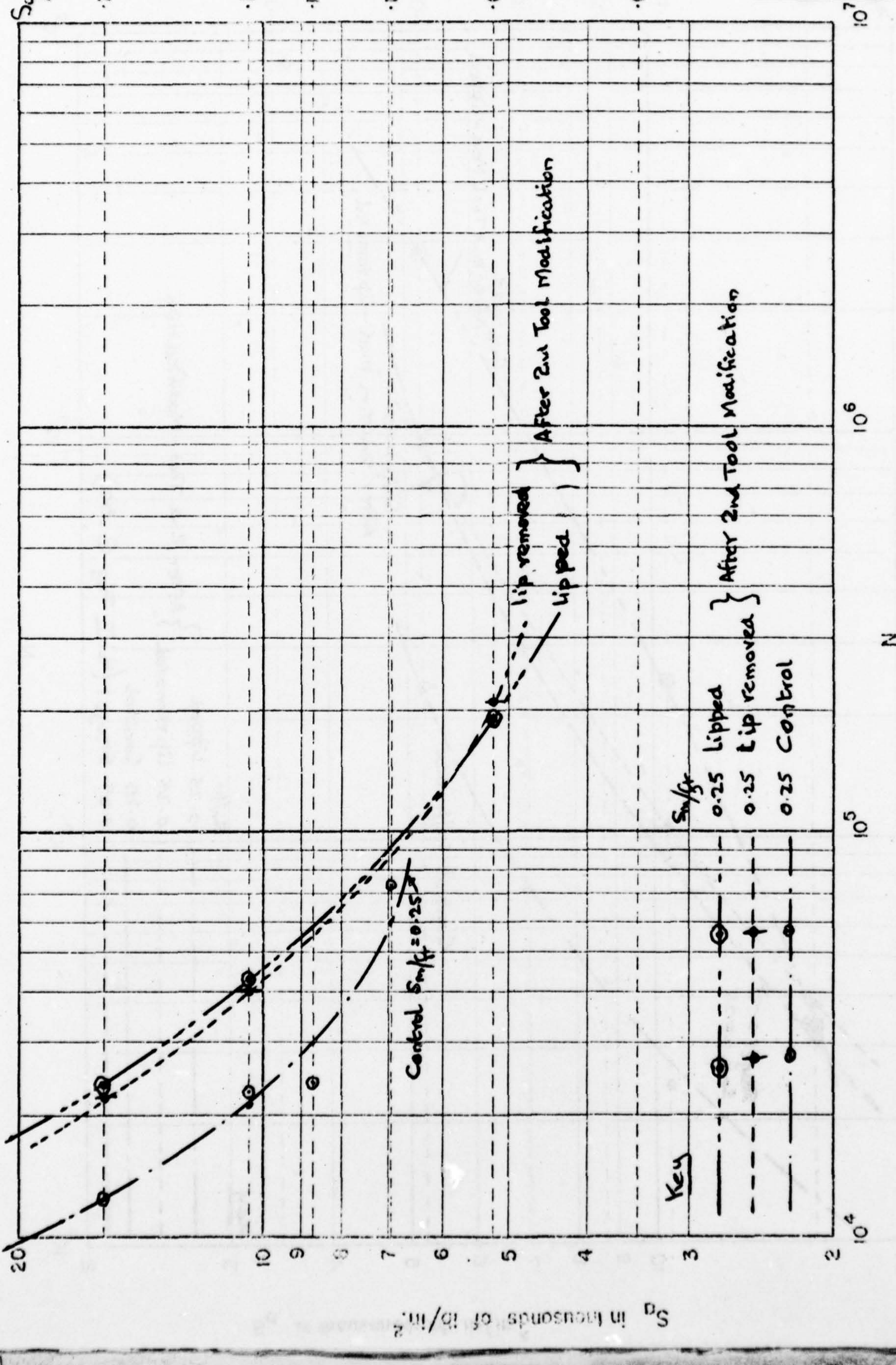


S.I. No 1

FIGURE 12 SPECIMENS TYPE 2D 15/32 PUSH FIT PIN PIN LOADED $d/D = 3/8$

RESULTS AFTER SECOND TOOL MODIFICATION

Ref. TABLE 8



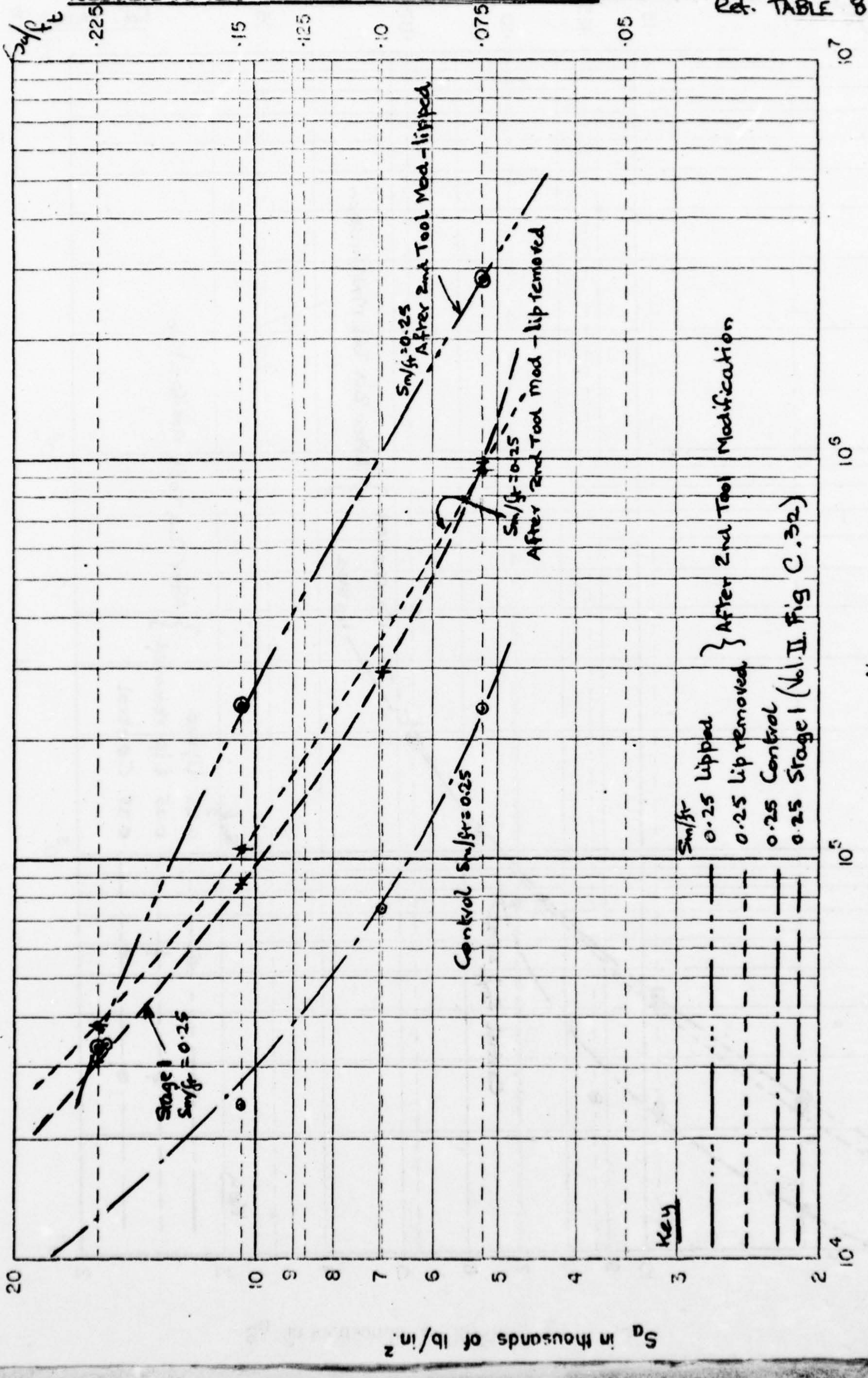
26

S.I. No. 7

FIGURE 13 SPECIMENS TYPE 2D5/8 PUSH FIT PIN PIN LOADED $d/D = 1/2$

RESULTS AFTER SECOND TOOL MODIFICATION

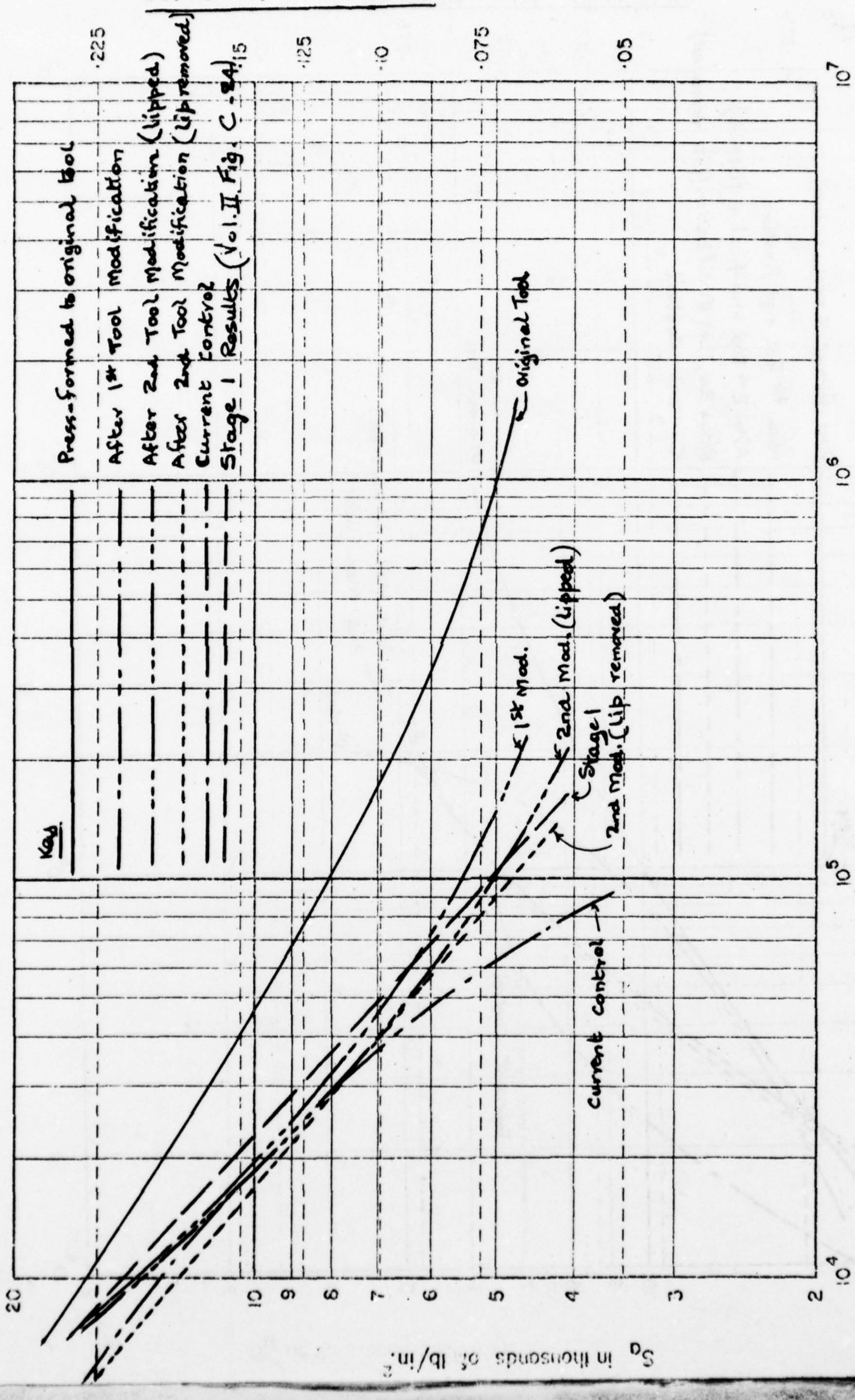
Ref. TABLE 8



S.1. No 7

FIGURE 14 SPECIMENS TYPE 2 B 5/16 $d/D = 1/4$ $S_m/f_t = 0{\cdot}25$

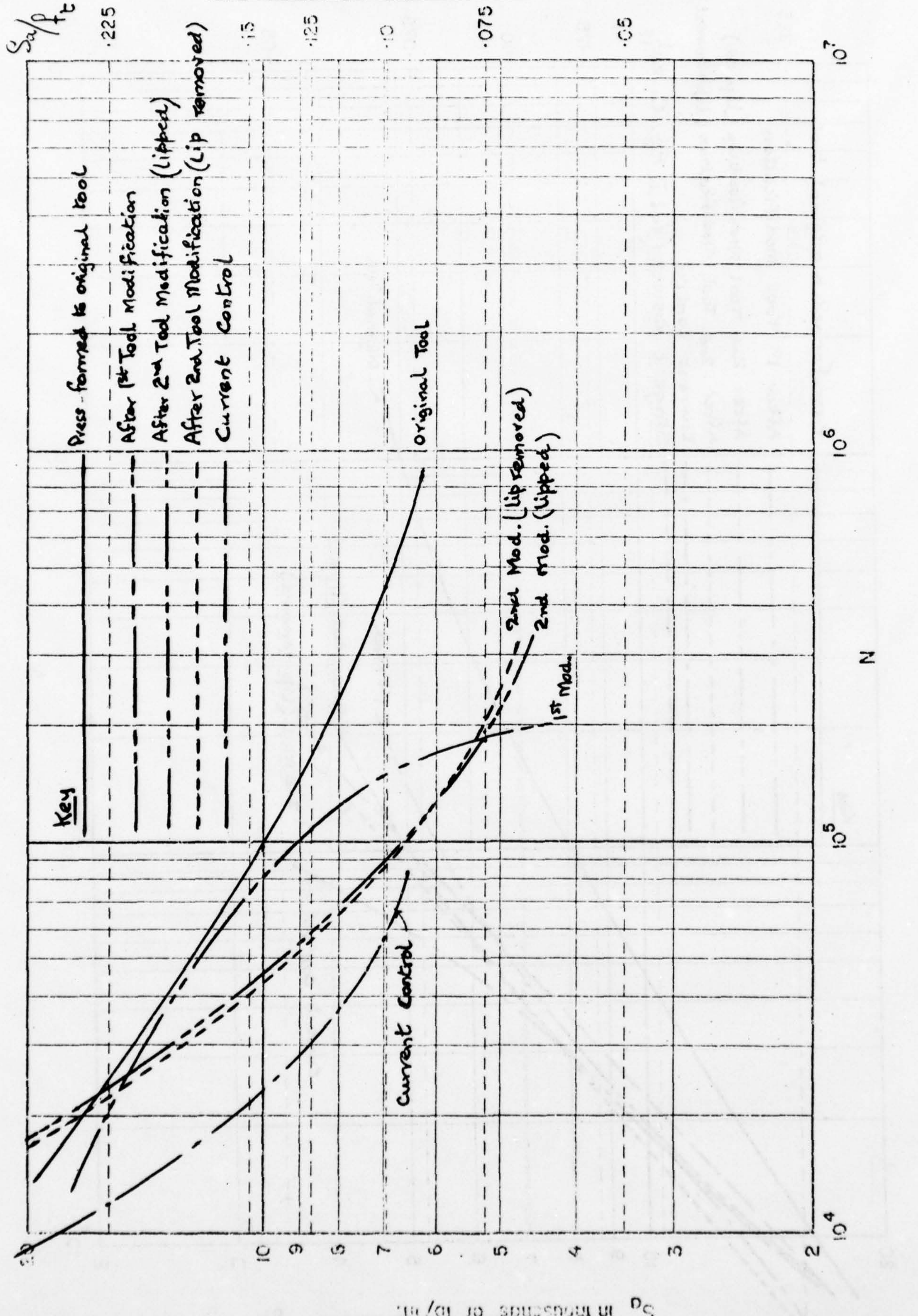
SUMMARY OF RESULTS



S.I. No 7

FIGURE 15. SPECIMENS TYPE $2D\frac{15}{32}$ $d/D = 3/8$ $S_m/f_t = 0.25$

SUMMARY OF RESULTS



S.1. No 7

FIGURE 16 SPECIMENS TYPE $2D^{5}/_{8}$ $d/D = \frac{1}{2}$ $S_m/f_t = 0.25$

SUMMARY OF RESULTS

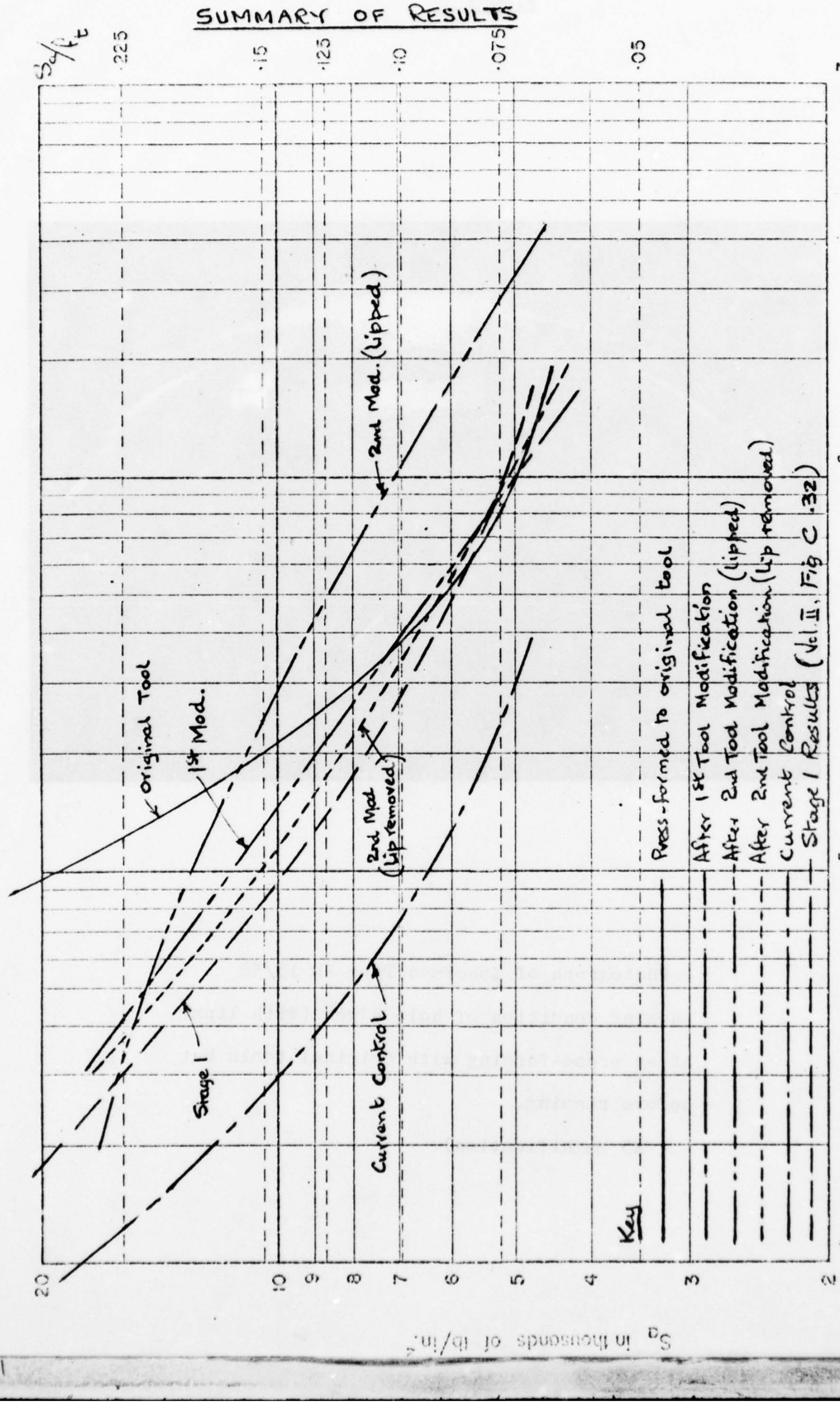
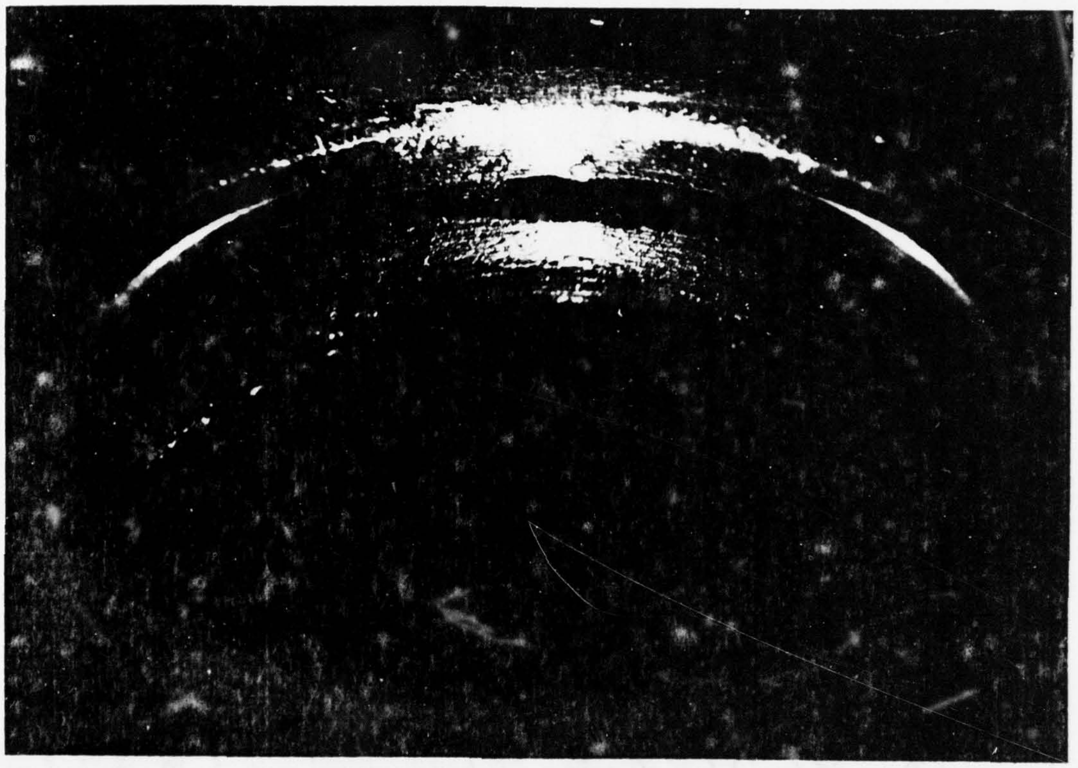


FIGURE 17



Photograph of Specimen Type 2D 15/32 showing condition of hole edges (with lips) after press-forming with original tools but before reaming.

(X5 Magnification)

SUPPLEMENTARY INVESTIGATION No.8

EXPOSURE TESTS ON STANDARD AND NON-STANDARD SPECIMENS AND SUBSEQUENT EFFECTS ON FATIGUE ENDURANCE

1. INTRODUCTION

Corrosion of vital parts of an aircraft structure is an ever present possibility. Moreover, where sustained assembly stresses are present due to interference fit pins, or where fatigue strengthening processes involve induced residual stress systems, stress corrosion cracking may occur, and the resulting fatigue endurances achieved in service may be less than those obtained under laboratory environment. Therefore it was considered that this programme of research would be enhanced if some standard specimens (i.e. Stage 1 types) and some non-standard specimens (i.e. Stage 2 types, Supplementary Investigations No.1, 3 and 7) were selected and subjected to exposure in a semi-marine atmosphere and examined from time to time for corrosion effects. Arrangements were made to do this, and half of the total number of each type of specimen was given the currently acceptable form of surface protection, and the other half was not given any protection treatment at all.

Subsequently after adequate exposure time and periodic inspections, specimens with both standards of preparation were fatigue tested and the resulting endurances analysed.

This present report has been compiled from a series of reports received from Short Brothers and Harland Ltd, over the period 1971 to 1976. (References 1 and 2).

2. NOTATION (Units are in lb and inches throughout)

For convenience the relevant Notation from the Stage 1 report is repeated below -

d	=	Nominal diameter of hole and pin
D	=	Width of parallel section of test specimen
f_t	=	Average Tensile Strength of plate material (from tests)
f_p	=	Average $0.2^o/o$ Proof Stress of plate material (from tests)
K_t'	=	Geometric stress concentration factor based on net area of cross section of test specimen

N = Endurance

S_m = Mean Stress on net area

S_a = Alternating stress on net area associated with S_m

t = Thickness of plate specimen

3. SPECIMEN TYPES (Standard and Non-standard)

These are all illustrated on Figure 1.

Almost all the specimens were either of the medium size or of the small size, i.e. with the prefix '2' or '4' respectively in the type number, although there were just a few specimens of the large size (prefix 1). All the illustrations in Figure 1 are drawn for the medium size but values of specimen width 'D' are given for the other sizes as well. The surfaces of all the specimens were in the "as rolled" condition.

3.1 Standard Specimens - as for Stage 1

These were all of the unloaded pin type - letter designation 'A' or 'C' and covering d/D = 1/4, 3/8 and 1/2. Specimens were provided with push fit, $0.4^o/o$ and $0.8^o/o$ interference fit pins for each value of d/D. The main group was of medium size, but a few specimens were also available in both large and small sizes, but only for d/D = 3/8 and with $0.8^o/o$ interference fit pins.

The allocation of specimens for each configuration and standard of preparation are given in Table 1.

3.2 Non-Standard Specimens

3.2.1 As for Supplementary Investigation No.1 i.e. Interference Pre-stressed Holes ("Ballising")

These were of the loaded pin types ('B' or 'D') covering the usual three values of d/D = 1/4, 3/8 and 1/2 and all specimens were of the medium size.

The holes were initially drilled for a push fit pin and then cold worked by forcing an oversized steel ball through the hole.

Two degrees of oversize were employed, namely $1^o/o$ and $4^o/o$. The allocation of specimens for each configuration and standard of preparation are given in Table 2A.

3.2.2 As for Supplementary Investigation No.3 i.e. Specimens Pre-loaded before Testing

All these specimens were of the loaded pin type ('B' or 'D'), all of the small size, and covering all three values of d/D. As with the standard specimens, push fit pin, $0.4^o/o$ and $0.8^o/o$ interference fit pin forms were

provided and for each of these two degrees of pre-stress were used, namely 0.75 f_t and 0.60 f_t. Table 2B gives the allocation for each configuration and standard of preparation.

3.2.3 As for Supplementary Investigation No.7

i.e. Push Fit Holes with Press Formed Radii at both edges

In this investigation also the specimens were all of the loaded pin type, and of the medium size, covering $d/D = 1/4$, $3/8$ and $1/2$. The press formed radii were made with the same tools as for the initial tests described in Supplementary Investigation No.7. Table 2C gives the allocation for each configuration and standard of preparation.

4. TEST PROCEDURE

4.1 Preparation of Specimens

The specimens in the "unprotected" half of each group of specimens were assembled dry in the "as received" condition with no other surface treatment for the plates, although the pins were cadmium plated. The specimens in the "protected" half of each group were given the following standard protective treatment:-

(a) Anodic treatment to D.T.D. 910 Section II.

(b) Two coats of chrometch (e.g. Titanine P.R. 30B)

(c) Two coats of paint (primer and final coat) to D.T.D. 5555 e.g. (Titanine TT16)

(d) "Duralac" or equivalent on assembly with the cadmium plated pin.

4.2 Exposure

All the specimens were exposed out of doors, with roof cover, in a semi-marine atmosphere, at the works of Short Brothers and Harland Ltd, Belfast and this firm monitored the tests throughout the whole programme. No load was applied to the specimens during the exposure period. The exposure period commenced at the end of July of 1970 and all the specimens were kept under observation throughout the ensuing months.

4.3 Examination of Specimens

After an exposure time of 159 days (approximately 5 months) the specimens without protective treatment were all showing evidence of corrosion and were removed from the exposure site for a detailed examination in the laboratory. This covered both visual inspection and inspection with the aid of a binocular

microscope at X40 magnification. Following the examinations it was felt advisable to select a limited number of unprotected specimens from each group and examine them metallurgically at strategic locations for evidence of cracks etc.

The specimens with protective treatment did not at this stage show any indications of corrosion. They were left for a further period and after a total exposure time of 370 days (approximately 12 months) they were removed and subjected to a detailed laboratory examination, including the use of a binocular microscope at X40 magnification. On none of these specimens was there any evidence of a breakdown of the paint film, nor of any apparent cracking.

All the specimens, except those unprotected ones which had been cut up for metallurgical examination, were returned to the exposure site and kept under observation for a further period of time.

After total exposure times of:

448 days (approximately 15 months) for the unprotected specimens and 688 days (approximately 23 months) for the protected specimens, they were removed and individually wrapped and stored under laboratory conditions pending fatigue testing. This storage period ranges from about one to three years for individual specimens. Just prior to fatigue testing a brief visual examination of the specimens was made.

The results of all these visual and metallurgical examinations are reported in paragraphs 5 to 8 inclusive.

4.4 Fatigue Tests on Exposed Specimens

The fatigue tests were carried out at Queen's University, Belfast using Amsler Vibrophore type machines of 5 and 10 Ton maximum capacity coupled with 2, 5 or 15 Ton dynamometers as appropriate to ensure maximum accuracy of loading. Testing was carried out at a frequency of 7200 c.p.m.

All of the specimens were tested at a mean stress of 0.25 f_t, except the interference fit pin specimens of Stage 1 type which were tested at a mean stress of 0.50 f_t. In each case two or three levels of alternating stress were employed. The results are given in Tables 9 to 12 and discussed in paragraph 9.

5. RESULTS OF EXAMINATION OF UNPROTECTED SPECIMENS AFTER AN EXPOSURE PERIOD OF 159 DAYS

All the specimens showed fairly uniform corrosion on the surfaces of the plates. In some specimens this corrosion extended right up to, and was in contact with the pin, but in the majority there was a ring of material around the pin on both sides of the plate, or on the pin entrance side only, which was relatively unattacked. These three types of corrosion are designated 1, 2 and 3 respectively and are described in Table 3 and illustrated in Figure 2A (type 1 - uniform corrosion up to pin) and on Figure 2B (types 2 and 3 - ring of material unattacked around pin).

For the pins, there were also three types of corrosion attack designated 1, 2 and 3 respectively, in which there was either uniform rusting of the pin (type 1), rusting where the cadmium was abraded locally (type 2), or the pin was relatively free from rusting (type 3). These types of corrosion are also described in Table 3, type 1 being illustrated in Figure 2A and type 3 in Figure 2B.

The distribution of the different forms of corrosion attack among the various specimens examined is recorded in Tables 4 to 7 as follows:-

Table 4	-	Stage 1 specimens		
Table 5	-	Supplementary Investigation	No. 1	specimens
Table 6	-	" "	No.3	"
Table 7	-	" "	No.7	"

They are discussed in the following paragraphs.

5.1 Standard Specimens - as Stage 1 (Table 4)

Reviewing the various types of corrosion attack on the plates and pins, they can be summarised thus:

Plate	Type	1	2	3	Totals
	No. off	7	17	6	30
	Percentage	23	57	20	100
Pin	Type	1	2	3	Totals
	No. of	7	19	4	30
	Percentage	23	64	13	100

Thus for the plates, approximately 60°/o showed a ring of relatively uncorroded material around the pin on both faces of the specimen. These included most of the push fit and a fair proportion of the 0.4°/o I.F. specimens. Few of the 0.8°/o I.F. specimens were in this category, probably due to substantial abrasion of the cadmium plating.

About one quarter of the specimens showed corrosion right up to the pin and of these all but one had interference fit pins.

For the pins, nearly two thirds were of type 2, i.e. where the only pin corrosion was at localities where the cadmium had become abraded. Approximately one quarter of the pins exhibited uniform rusting and these were invariably associated with the total corrosion of the plate, with the larger ratios of d/D, and all but one were on interference fit pins.

5.2 Non-Standard Specimens - as Supplementary Investigation No.1 (Table 5)

In these specimens, all the plates exhibited corrosion attack of the type 2, i.e. with an almost completely unaffected ring around the pin, on both surfaces. Also there was only a limited amount of corrosion along the edges of these (and other specimens) where they had been filed and finished with emery cloth. The specimens for this particular Supplementary Investigation had also been filed and finished with emery locally around the hole edges, to remove the metal raised by the "ballising" process. It follows therefore that the freedom from corrosion around the pin is due in part to the exposed base metal surface which appears to offer a better corrosion resistance than the rolled surface. The other contribution to the corrosion free ring is of course the cathodic protection due to the vicinity of the cadmium plated pin, but this can be lost locally where the cadmium is abraded.

For the pins the types of corrosion are well distributed among the samples examined, thus:

Type	1	2	3	Totals
No. off	8	4	6	18
Percentage	44	23	33	100

Therefore nearly half of the pins were uniformly rusted, one third were relatively free from rust and one quarter were only rusted where cadmium abrasion had occurred.

In general those specimens which were cold worked with a $4^{o}/o$ oversize ball had less corrosion than those with a $1^{o}/o$ oversize ball.

5.3 Non-Standard Specimens - as Supplementary Investigation No.3 (Table 6)

Here the distribution of corrosion attack was as follows:

	Type	1	2	3	Totals
Plate	No. off	11	25	nil	36
	Percentage	30	70	nil	100
Pin	Type	1	2	3	Totals
	No. of	3	16	17	36
	Percentage	8	45	47	100

Thus for the plates, approximately one third were fully corroded up to the pin, and this feature tended to be among the specimens with low values of d/D (Type 4 B3/16). Also all specimens of this type had bearing failures of the holes, resulting in a clearance between the pin and the plate. In the interference fit specimens of this same group, with 0.60 f_t pre-stress, partial rings occurred where the pin made local contact with the hole edge. Nearly all the specimens with d/D = 3/8 and 1/2 showed corrosion attack of the type 2.

The pins in this group were almost equally divided into corrosion types 2 and 3, and type 3 (no rusting) was predominant in the 4 B3/16 specimens, i.e. the ones with the bearing failures.

5.4 Non-Standard Specimens - as Supplementary Investigation No.7 (Table 7)

For these specimens the distribution of corrosion attack was:

Plate	Type	1	2	3	Totals
	No. of	2	4	nil	6
	Percentage	33	67	nil	100
Pin	Type	1	2	3	Totals
	No. of	4	2	nil	6
	Percentage	67	33	nil	100

Although the number of specimens was small, it would appear that the plates were largely prevented from serious corrosion at and around the pins by virtue of the removal of the rolled surface by the press-forming tools and by the subsequent reaming of the holes to obtain a push fit. (See remarks in paragraph 5.2).

The pins suffered more extensive corrosion, perhaps due to cadmium abrasion during assembly.

5.5 Examination by Binocular Microscope

Following the visual examination of all specimens, those which exhibited the most severe corrosion were selected for further review, using a X40 binocular microscope. The specimens were brushed lightly in the vicinity of the pin holes and then examined for cracks. Although pitting was apparent, no cracks were detected by this method, on any of the plates.

6. METALLURGICAL EXAMINATION OF SELECTED SPECIMENS

(After 159 days exposure)

Notwithstanding the findings related above, it was considered advisable to pursue the examination further, at least for the most corroded of the unprotected specimens, and subject them to a metallurgical examination. The specimens chosen have been anotated in Tables 4, 5, 6 and 7 and are separately listed in Table 8 which gives also the reasons for their selection.

6.1 Preparation of Micro-Specimens

A rectangle of material, generally from the area surrounding the pin, was cut from each specimen. The excess pin length of the specimens concerned was cut off and the pin ground until nearly flush with the plate surface prior to preparation for micro-examination. This allowed the plate adjacent to the pin to be examined in a direction normal to the plate and within a few thousands of an inch from the surface, as preparation for micro-examination had been accomplished with a minimum removal of material.

6.2 Results of Micro-Examination

6.2.1 Standard Specimens (as Stage 1)

On the four specimens examined, pitting and intercrystalline attacks extended to the hole edge. Many intercrystalline networks at the hole edge or in close proximity to the hole edge, tended to extend more in a radial direction than to spread circumferentially. The limiting case of this produced a crack-like feature as shown in Figure 3. These are considered to be cases of incipient stress corrosion cracking.

An example of extensive intercrystalline corrosion with associated pitting is shown on Figure 4. Specimen 13.26.J was sectioned in a transverse direction approximately 0.5 in. away from the hole, and the maximum depth of corrosion penetration measured as 0.006 in. The corrosion was frequently of a marked layered nature.

6.2.2 Supplementary Investigation No.1 Specimens

The two specimens examined were free from cracking. Pitting attack and intercrystalline corrosion was present outside a ring of material approximately 1.4d around the pin, which remained virtually free from attack. This confirms the visual and binocular observations.

6.2.3 Supplementary Investigation No.3 Specimens

The three cases examined exhibited areas surrounding the pin which were relatively free from the pitting and intercrystalline attack prevalent elsewhere on the plate surface, the hole edges being particularly free.

On specimen 22.12.N however, what are considered to be incipient stress corrosion cracks similar to those shown on Figure 3 were found in close proximity to the hole edge on the longitudinal axis.

Transverse intercrystalline cracks were found on the plate surface of specimen 22.12.N in the region of the minimum width, but remote from the hole, suggesting the presence of residual tensile stresses reacting the residual

compressive stresses near to the hole, and developed during the pre-stressing operation. A typical example and its location is shown on Figure 5. A section was taken through one of the cracks which was found to have penetrated to a depth of approximately 0.006 in. but with no apparent opening. Relatively few of the cracks had been initiated at the edge of the plates. Similar transverse cracks were found on specimen 22.12.E.

The grain structure of the plate was fairly equiaxed so that the transverse direction at the location of the cracks was not necessarily incompatible with incipient stress corrosion cracking.

6.2.4 Supplementary Investigation No.7 Specimen

This specimen exhibited pitting and intercrystalline corrosion extending to the hole edge, but no cracking was apparent.

7. SUBSEQUENT VISUAL EXAMINATION AFTER EXPOSURE BUT JUST PRIOR TO FATIGUE TESTING

The further visual examination of all the specimens made just prior to the fatigue testing i.e. after 448 days exposure for the unprotected specimens and after 688 days exposure for the protected specimens, revealed the following facts.

(i) Of all the specimens with types 2 and 3 corrosion of the plates, i.e. with a relatively unattacked ring of material around the pin after 159 days exposure, $85^{o}/o$ of them showed that the corrosion had extended up to the hole edges as for type 1.

(ii) Of all the pins with types 2 and 3 corrosion, $60^{o}/o$ of these could now be listed as type 1, i.e. "uniformly rusted" apart from the bearing area of the interference fit pins, where the cadmium plating was still present.

(iii) The general appearance of the unprotected specimen surfaces showed that there had been some further deterioration, the depth of which was determined but which would be consistent with the spread of the corrosion around the pins.

(iv) No corrosion was reported at this stage on the specimens with full protective treatment.

8. CONCLUSIONS REGARDING SPECIMEN EXAMINATIONS DURING AND AFTER EXPOSURE BUT PRIOR TO FATIGUE TESTS

(i) None of the specimens which had had the standard protective treatment exhibited any corrosion after 370 days exposure, nor apparently after 688 days exposure, (but see paragraphs 10.3, 11(vi) and 12(i)).

(ii) Practically all of the specimens which were unprotected suffered corrosion on the plates after 159 days exposure, but between 60°/o and 75°/o of each type of specimen exhibited a narrow ring around the pin which was relatively free from corrosion. This was partly due to electrolytic action between the cadmium plated pin and the plate, and partly due to the plate material adjacent to pin being in some cases filed, thus exposing the bare material which, from the appearances of the plate edges which were likewise filed, was apparently more corrosive resistant than the rolled surface of the plate. However after 448 days exposure this relatively unattacked ring had become corroded on 85°/o of the samples.

(iii) For the pins, after 159 days exposure, between 60°/o and 90°/o had little or no corrosion, presumably chiefly because of the cadmium plating. In a few instances, particularly for the I.F. pins, limited corrosion occurred because the plating had been abraded locally during assembly. However, after 448 days exposure corrosion had enveloped more than half of this group of pins.

(iv) No cracks were found in the plates, either by normal vision or by use of a binocular microscope (X40). However when the most seriously corroded specimens were examined metallurgically, intercrystalline corrosion and incipient stress corrosion cracks were visible on a number of the specimens examined.

N.B. For conclusions regarding micro-examination of fatigue failures, see paragraph 11 and for Final Conclusions on the full programme of tests see paragraph 12.

9. FATIGUE TEST RESULTS

After the extended exposure tests all of the specimens were subjected to fatigue tests except those used for the metallurgical examination.

The results of these tests are presented in Tables 9 to 12 and graphically in Figures 6 to 31. Each table is cross referenced to its corresponding figure and vice versa.

Table 9 covers all the standard (Stage 1) type specimens and is sub-divided into parts A to E to correspond to the five types of specimen defined in Table 1.

Tables 10, 11 and 12 deal with non-standard specimens and correspond respectively to the three groups of Tables 2A, 2B and 2C, - i.e. to specimens of the three types Supplementary Investigation No.1, No.3 and No.7. Furthermore each one of Tables 10, 11 and 12 is subdivided into parts A, B, C --- etc., to cover each specimen type listed in Tables 2A, 2B and 2C.

In plotting these fatigue test results, they have been divided into as many as 26 separate figures in order to avoid confusion between the various specimen groups and types, but the cross references enable one readily to select the corresponding tables and figures.

For convenience the plotting codes for these fatigue test results are given below, as well as on the relevant figures. They are divided into four groups.

(a) Stage 1 type specimens

Reference Table 9 (A B C D and E) Figures 6 to 16

NB where I.F. is used for interference-fit pins

Unprotected

Push Fit

$0.4^{o}/o$ I.F.

$0.8^{o}/o$ I.F.

Protected

Push Fit

$0.4^{o}/o$ I.F.

$0.8^{o}/o$ I.F.

Stage 1 Data

Push Fit

$0.4^{o}/o$ I.F.

$0.8^{o}/o$ I.F.

(b) Supplementary Investigation No.1 Type Specimens

Reference Table 10 (A B and C) Figures 17, 18 and 19

Unprotected

$1^{o}/o$ Oversize ball

$4^{o}/o$ Oversize ball

Protected

$1^{o}/o$ Oversize ball

$4^{o}/o$ Oversize ball

Supplementary Investigation No.1 Data

$1^{o}/o$ Oversize ball

$4^{o}/o$ Oversize ball

(c) Supplementary Investigation No.3 Specimens

Reference Table 11 (A B C D E and F) Figures 20 to 28

Unprotected - 0.75 f_t pre-load

As for Stage 1 unprotected specimens

Unprotected - 0.60 f_t pre-load

As for 0.75 f_t but lines hatched thus

Protected - 0.75 f_t pre-load

As for Stage 1 protected specimens

Protected - 0.60 f_t pre-load

As for 0.75 f_t but lines hatched thus

Supplementary Investigation No.3 Data

At 0.75 f_t pre-load - as for Stage 1

At 0.60 f_t pre-load - as for Stage 1 but lines hatched.

(d) Supplementary Investigation No.7 Type Specimens

Reference Table 12 (A B and C) Figures 29, 30 and 31

Unprotected

4.0 tons press tool load

4.5 " " " "

5.0 " " " "

Protected

4.0 tons press tool load

4.5 " " " "

5.0 " " " "

Supplementary Investigation No.7 Data

4.0 tons press tool load

4.5 " " " "

5.0 " " " "

9.1 Discussion of Fatigue Test Results

General

A study of these tables and figures makes it abundantly clear that the corrosion, and in some cases the pitting and incipient cracking, which occurred on the unprotected specimens generally reduced the fatigue endurances when compared with those of the corresponding protected specimens. Only the Stage 1 type specimens at $d/D = 3/8$ gave results which were not consistent with this characteristic, but even so the relationship between the protected and unprotected specimens was only just reversed, generally at the higher values of S_a. The actual extent of this general reduction in endurance due to corrosion has been evaluated for each group and type of specimen and is presented in Tables 13 to 16 inclusive.

In addition, where data is available, the opportunity has been taken to compare the fatigue endurances of the protected specimens of this programme with those of the corresponding specimens in Stage 1 or in the Supplementary Investigations as appropriate. The results of these comparisons are also given in Tables 13 to 16 inclusive, and are not always as good as was expected. It must be remembered, however, that in this present programme only one specimen per stress level was tested compared with three per stress level in the Stage 1 and the Supplementary Investigation test programmes. Furthermore, it is recalled that in the Stage 1 and Supplementary Investigation programmes the specimens had been treated with a stripable transparent lacquer, wrapped in brown paper, and stored in a dry building prior to testing, and then at the time of testing were stripped and just coated with lanolin grease. Thus, agreement or otherwise between the endurances of these and the protected specimens of the current programme would depend upon the efficiency of this method of storage and temporary protection during testing, in comparison with full protection.

The following sub-paragraphs (9.1.1 to 9.1.4) comment on each group in respect of these two evaluations.

9.1.1 Stage 1 Type Specimens (Table 13)

All these specimens were of the unloaded pin form.

Detailed particulars and mean stresses are given in the first four columns of this table. Column 5 quotes for each configuration a range of values for the ratio:-

$$\frac{\text{Endurance of unprotected specimens}}{\text{Endurance of protected specimens}}$$

This ratio gives a measure of the penalty incurred for the omission of an adequate standard of protective treatment. The first ratio of the range refers to tests at high values of S_a and the second ratio of the range to low values of S_a. The variation between the two is not necessarily linear, and there is more scatter of values at low alternating stresses than at the high alternating stresses.

For the Stage 1 type specimens the endurance ratio for those with $d/D = 1/4$ ranges from 0.8 to 0.5. For $d/D = 3/8$, the ratio extends to beyond unity at high alternating stresses and to a lower value than for $d/D = 1/4$ at low alternating stresses. Thus for $d/D = 3/8$ there is a maximum range from 1.5 to 0.1 although 1.3 to 0.4 would apply more generally.

For $d/D = 1/2$ it is not easy to be precise because of the greater scatter of results and because there are some regions where the data yields results beyond endurances of 10^7 cycles, but the endurance ratio is certainly as wide as 0.7 to 0.2,

There is no significant difference between the endurance ranges for the three degrees of pin fit included in these tests.

In regard to the comparisons between the endurances of the protected specimens and those of the corresponding Stage 1 specimens (see Column 6 of Table 13) the agreement is only fair, but acceptable in the light of the variation in number of specimens tested at each stress level and degree of protection provided - see paragraph 9.1 above.

A check against the appropriate Stage 1 endurance plots shows that about 50°/o of the present results fall within the scatter of the Stage 1 results and 50°/o fall outside that scatter.

9.1.2 Supplementary Investigation No.1 type specimens (Table 14)

These were all of the loaded pin form. Table 14 is arranged in a form similar to Table 13 and the endurance ratios indicating the penalty for lack of protection tend to be slightly more consistent at $d/D = 3/8$ and $1/2$, when compared with Stage 1 types. It is possible that slightly greater ranges would have been found if more specimens had been tested.

There is no real difference between 1°/o and 4°/o oversize ball endurance ratios, and an over-all range applicable to all these values of d/D and to both degrees of oversize of the ball might be quoted as 0.8 to 0.3.

The comparisons between the protected specimen endurances of this Supplementary Investigation and those of the Supplementary Investigation No.1 are again only fair, and once more approximately 50°/o of the results fall outside, and 50°/o fall inside the scatter band of the original Supplementary Investigation No.1 specimens.

9.1.3 Supplementary Investigation No.3 type specimens (Table 15)

All these specimens were of the loaded pin form.

There was no significant difference between pre-stresses of $0.75\ f_t$ and $0.60\ f_t$.

At $d/D = 1/4$, the penalties for the omission of protective treatment were fairly consistent, but of somewhat lower order than for Stage 1, endurance ratios ranging from 0.8 to 0.2. This was probably due to the bearing failures noted in paragraph 5.3 and on Tables 11A and 11B.

At $d/D = 3/8$, as with Stage 1 type specimens, the range of endurance ratios was wider than at $d/D = 1/4$, not extending beyond 0.8 at high S_a but down to 0.1 at low S_a.

At $d/D = 1/2$ the effect of the corrosion was considerable, leading to endurance ratios ranging from 0.4 to 0.1 and possibly lower.

Comparisons between the endurances of these protected specimens and previous Supplementary Investigation No.3 specimens showed a wide variation, with less consistency than for the two preceding types. A check against the variability of results for the original Supplementary Investigation No.3 specimens showed that only $40^{o}/o$ of the results of the present tests lie within the scatter of the original tests and $60^{o}/o$ were outside that range. This suggests that the two sets of results could be regarded as belonging to different populations, possibly for the reasons discussed in paragraph 9.1.

9.1.4 Supplementary Investigation No.7 type specimens (Table 16)

These specimens were also of the loaded pin form.

The small amount of data available was not sufficient to enable reliable conclusions to be drawn, but the general trends appeared to be similar to those applicable to the other groups of specimens.

It is recalled that the Supplementary Investigation No.7 type of specimen had proved to be very sensitive to press tool design. Checking the current endurances against the original Supplementary Investigation No.7 results showed that none of the current results came within the scatter band of the original endurances, and again the two populations are dissimilar.

10. EXAMINATION OF FAILED SPECIMENS

Following the fatigue tests a considerable number of specimens were examined under a low power microscope - <X60, and a smaller number were subjected to micro-examination at X63 or X125, the former group being indicated thus - ✓ and the latter thus - ✗ in the tables of fatigue results (Tables 9 to 11). The specimens selected for the higher power micro-examinations are also listed in Figure 32 which gives details of the micro-specimen locations.

The following paragraphs summarise the observations of this examination.

10.1 Standard Specimens - as Stage 1 (Variation of Pin Fit)

All the specimens tested at $0.50\ f_t \pm 0.225\ f_t$ (with the exception of 2A5/16, $d/D = 1/4$, $0.4^{o}/o$ Interference Fit) failed predominantly from primary sites at the edges of the specimens in the region of the transverse centre line.

Specimens tested at 0.50 f_t mean stress but with lower alternating stresses, and those tested at 0.25 f_t mean stress (push fit) generally failed from primary sites at the hole edges just behind the transverse centre line (at clock notation 9.30 and 2.30 - see Figure 32) and sometimes with evidence of light fretting.

The failed unprotected specimens exhibited multiple transverse cracking of the plate surfaces at the transverse centre line. When the failures propagated from the holes, the surface cracking intensified within the proximity of the specimen edge, but this situation became reversed when cracking propagated from the specimen edge, thus suggesting that the transverse surface cracking is associated with fissuring of the intergranular corrosion sites in way of the fatigue crack stress field.

This was confirmed by the micro-examination of specimen 26.16.C (2A 5/16, Push Fit, low S_a) sectioned as shown at Figure 32(a) and 0.02 in removed from face A, which showed this fissuring; and of specimen 24.2.D (2A 5/16, 0.8^o/o Interference Fit, low S_a) sectioned as shown at Figure 32(c), at faces A and B, where the transverse centre line edge location had not been subjected to the high stresses associated with extensive fatigue cracking, and which showed the characteristic layered intercrystalline corrosion without fissuring. Another specimen, 24.1.E (2A 5/16, 0.8^o/o Interference Fit, high S_a) i.e. failed at the highest stress level, was also sectioned as Figure 32(a) face A and exhibited numerous fatigue cracks emanating from the corroded surface even at positions relatively remote from the transverse centre line (see Figure 33). No surface fatigue cracking was found on micro specimens extracted from joint plates tested below the 0.50 $f_t \pm 0.225$ f_t level.

Specimen 13.27.F (unfailed 4C9/32, 0.8^o/o Interference Fit, low S_a) was examined for surface corrosion around the hole edge and showed intercrystalline corrosion with a preference for radial growth with minimal lateral spreading, suggesting incipient stress corrosion activity, particularly in the transverse centre line locality and to within 0.05 in from the specimen edge (see Figure 34). It is thought possible that the "as rolled" surface in the presence of residual stresses is susceptible to stress corrosion cracking.

The bores of the holes were relatively free from corrosion,

10.2 Non-Standard Specimens - as Supplementary Investigation No.1 (Interference pre-stressed Holes)

The majority of specimens fatigued on both sides of the hole, near the transverse diameter with only a little evidence of fretting. Initiation was from the hole edges or occasionally from abraded areas of the bores in the 4^o/o interference

pre-stressed specimens. The unprotected specimens exhibited the transverse surface and edge cracking compatible with fissuring of intercrystalline corrosion sites in the way of the fatigue cracking. Multi-initiation frequently produced stepped fractures. Specimen 9.13.B (unprotected 2 D 15/32, $4^{o}/o$ interference pre-stress, fatigued at 0.25 f_t $\pm$0.075 f_t stress level) was lightly surface abraded and polished for micro examination. Established fatigue cracking was found at the hole edge but no stress corrosion activity was apparent.

10.3 Non-Standard Specimens - as Supplementary Investigation No.3 (Axial Pre-loading)

All the specimens fatigued on both sides near the transverse diameter (9 and 3 clock notation of Figure 32), with no obvious fretting influence. Initiation was in all cases from the hole edges and/or bores. Multi-initiation frequently produced stepped fracture faces (see Figure 35). However, all the unprotected specimens also exhibited multiple transverse cracking from the plate edges and adjacent surfaces at the transverse centre line.

A micro specimen (as Figure 32a) was extracted from specimen 12.11.N (unprotected 4B 3/16, $60^{o}/o$ Pre-load, Push Fit) to investigate this surface cracking near the specimen edges. Severe intercrystalline cracking was found in the region of the transverse centre line (see Figure 36). Three micro specimens were cut from specimen 21.3.J (see Figure 32b) - unprotected 4D 9/32, $60^{o}/o$ pre-load, $0.8^{o}/o$ Interference Fit). This specimen was unfailed so that the transverse centre line edges had not been subjected to high fatigue cracking stresses. Nevertheless the central micro specimen showed intercrystalline cracking on surface B. The earlier examination after 159 days exposure had shown stress corrosion activity attributed to a tensile residual stress system, near but not at the specimen edge. Therefore the presence of stress corrosion cracking on the least susceptible push fit, $60^{o}/o$ f_t case (12.11.N) suggests that all the unprotected Supplementary Investigation No.3 types would be so affected.

Several of the protected specimens showed indications of corrosion activity under the paint in way of the transverse centre line. Removal of the paint from some of the specimens revealed an incipient corrosive attack. It is possible that this feature could have been initiated by a partial loss of adhesion paint when the pre-load was applied. There were also a few cases of incipient transverse cracking of the type exhibited by the unprotected specimens, but a cut-up of specimen 21.3.A (protected push-fit high S_a) as Figure 32(a) showed these to be fissures in intercrystalline corrosion sites as a consequence of high stresses developed during the fatigue cracking process.

Among the specimens with $d/D = 1/2$ (4 D 3/8) there was a greater tendency to fatigue from one side, and for the protected specimens to fail from the edge at the highest stress level ($0.25\ f_t \pm 0.225\ f_t$).

10.4 Non-Standard Specimens - as Supplementary Investigation No.7 (Press formed Radii)

Specimens fatigued on both sides at the transverse diameter with initiations in the bore and at the edges, with secondary fatigue cracks on the lips resulting from the press forming operation. Specimen 14.4.D (protected, 2D 15/32, Stress level $0.25\ f_t \pm 0.225\ f_t$) was lightly surface abraded and polished for micro examination. No stress corrosion cracking was apparent but many incipient fatigue cracks and a few well established fatigue cracks emanated from the hole forward of the transverse diameter.

The fractured specimen 28.9.C (unprotected, 2D 5/16, stress level $0.25\ f_t \pm 0.225\ f_t$) was similarly prepared and showed fatigue cracks on the lips resulting from the press forming operation, and again at corrosion sites away from the hole.

11. CONCLUSIONS REGARDING MICRO-EXAMINATION OF FATIGUE FAILURES

(i) Specimens tested at the highest stress levels ($0.50\ f_t \pm 0.225\ f_t$ in the Stage 1 type, and some at $0.25\ f_t \pm 0.225\ f_t$ in both Stage 1 type and Supplementary Investigation No.7 type) failed predominantly from primary sites at the edges of the specimens whereas specimens tested at lower stress levels failed from the hole edges.

(ii) For the unprotected specimens the micro-examination showed a definite fatigue-corrosion interaction coupled with some stress corrosion-fatigue interaction in those specimens containing residual stress systems either due to pin interference or to the application of pre-stressing in some forms with intent to delay the onset of fatigue.

(iii) In specimens tested at high stress levels where fatigue cracks were initiated from the edges (particularly the Stage 1 types) there were multiple transverse cracks on the plate surfaces at the transverse centre line, with associated fissuring of the intergranular corrosion sites in way of the fatigue crack stress field.

(iv) In a number of specimens (generally the Stage 1 types with Interference Fit pins, Supplementary Investigation No.1 types and some of the Supplementary Investigation No.7 types) where crack intiation was from the hole edges there was intercrystalline corrosion around the hole with a preference for radial growth rather than lateral growth suggesting incipient stress corrosion activity.

Comparable stress corrosion activity was also observed from other surfaces away from the hole, suggesting that the "as rolled" surface in the presence of residual stresses is susceptible to stress corrosion cracking.

(v) Although the primary failures of the Supplementary Investigation No.3 types were at the hole edges and/or bores, the unprotected specimens also exhibited some multiple transverse cracking from the plate edges and adjacent surfaces at the transverse centre line.

(vi) The protected specimens of all types generally showed that the protection did provide freedom from corrosion and stress corrosion activity. However, some local breakdown of the paint protection did occur in several specimens of the Supplementary Investigation No.3 type, allowing mild corrosive attack which may have accounted for a significant reduction of endurances in these cases.

It is possible that this feature could have been initiated by a partial loss of adhesion of the paint when the pre-load was applied.

(vii) In the four groups discussed in paragraph 10, practically all the specimens other than those used for the fracture analysis had fatigue failures originating from the hole.

12. FINAL CONCLUSIONS ON THE FULL PROGRAMME OF TESTS

(i) Unprotected and paint protected elemental pinned joints of the types tested in both Stage 1 and Stage 2 of the Royal Aeronautical Society Bolted Joint Fatigue Research had been exposed without external loading to a semi-marine atmosphere and periodically examined.

After 159 days the majority of the unprotected specimens showed evidence of corrosion on the plate surfaces. No cracks were found on the plates by visual observation, nor by the use of a binocular microscope (at X40). However, further micro-examination of the most seriously corroded specimens revealed a limited amount of intercrystalline corrosion and some incipient stress corrosion cracks.

To a lesser extent, about one third of the cadmium plated pins exhibited some degree of rusting.

After a total of 448 days the corrosion on both the plates and the pins had become more extensive on $85^{o}/o$ of the plates and on $60^{o}/o$ of the pins.

The protected specimens were examined similarly after 370 days and again after a total of 688 days. There was no visual sign of any corrosion or cracking at 370 days nor generally after 688 days. Nevertheless during the fracture analysis after fatigue testing there were some cases of breakdown of the paint

protection revealing mild corrosion at some fatigue critical areas. The specimens concerned were all of the Supplementary Investigation No.3 type and it is thought possible that this feature could have been initiated by a partial loss of paint adhesion when the pre-load was applied.

(ii) Following the exposure tests, all specimens not cut up for the micro-examination were fatigue tested and almost without exception the unprotected specimens failed at a lower endurance than the corresponding protected specimens. The few which were not consistent with this statement were only marginally so, and could be explained by the fact that only one specimen per stress level was available for test.

(iii) The extent of the penalty for the omission of adequate protection of the specimen surfaces has been assessed by evaluating the endurance ratio, expressed as:

$$\frac{\text{Endurance of unprotected specimens}}{\text{Endurance of protected specimens}}$$

For the four types of specimen considered the following table summarises the approximate range of endurance ratios, for the three values of d/D included in the test.

Type of Specimen	d/D		
	1/4	3/8	1/2
Stage 1	0.8 to 0.5	1.3 to 0.4	0.7 to 0.2
S.I. No.1	0.8 to 0.3	0.8 to 0.3	0.8 to 0.3
S.I. No.3	0.8 to 0.2	0.8 to 0.1	0.4 to 0.1
S.I. No.7	0.6 to ?	?	?

NB

"?" signifies that there was insufficient data to enable endurance ratios to be quoted.

S.I. Supplementary Investigation.

The first ratio in the ranges quoted refers to high S_a and the second ratio to low S_a, but these are approximations since each ratio varies towards the other (see Tables 13 to 16). Notwithstanding this variability it appears that there was more consistency and less scatter at d/D = 1/4 (high stress concentration factor) than at d/D = 1/2 (low stress concentration factor).

There appeared to be no significant difference between loaded and unloaded pin types of specimen, nor yet between push fit and the two degree of interference fit pin in respect of the above endurance ratios (for Stage 1 and Supplementary Investigation No.3 types).

(iv) Concerning comparisons between the endurances of the protected specimens of this investigation and the corresponding specimens of Stage 1 or the previous supplementary investigations, agreement at best was only fair (e.g. at $d/D = 1/4$ in most configurations and at some other values of d/D for Stage 1 and Supplementary Investigation No.1 only) whereas for the remainder of results, especially those for Supplementary Investigation No.3 and No.7, there was little or no agreement.

Plotting the scatter of results of the current programme on the related original endurance plots has shown that only 50°/o of the current results for Stage 1 and Supplementary Investigation No.1 types fall within the scatter of the original data; that only 40°/o of the current results for Supplementary Investigation No.3 types fall within the original scatter band and not any of the current results for the Supplementary Investigation No.7 types are within the original scatter band.

It appears therefore, that the differences in preparation before testing and in protective treatment during testing, coupled with the exposure of the current specimens, justifies regarding the two groups of specimens as of different populations. It is also noteworthy that all the specimens of the current series were tested on one type of testing machine, whereas many of the original tests were made on fatigue testing machines of a different type or capacity (or both).

(v) A final macro and micro-examination of the failed specimens showed that those tested at a stress level of $0.50\ f_t \pm 0.225\ f_t$ failed predominantly from primary sites at the edges of the specimens (e.g. in the Stage 1 types). Similar failure characteristics were observed for most of the specimens tested at a stress level of $0.25\ f_t \pm 0.225\ f_t$ in Supplementary Investigation No.1 and No.7 types. For the majority of all other specimens (tested at lower alternating stress levels) the failure was initiated at the hole.

For the unprotected specimens there was a definite fatigue-corrosion interaction, coupled with some stress corrosion - fatigue interaction due to the presence of residual stresses (as with interference fit pins) or to superimposed stress systems (as with Supplementary Investigations No.1, No.3 and No.7).

In a number of the specimens tested at low stress levels, stress corrosion cracks away from the sites of crack initiation but near the surface suggest that "as rolled" surfaces may increase susceptibility to this form of cracking.

For the protected specimens, the standard protective treatment generally proved adequate, but in several of the Supplementary Investigation No.3 type specimens (pre-loaded before fatigue testing) some breakdown of the paint protection did occur, which resulted in mild corrosive attack and a significant drop in endurance. It is possible that the pre-load could have been responsible or partly responsible for the breakdown of the paint adhesive.

REFERENCES

1. - Progress Reports from Short Brothers and Harland Ltd, as follows

(a) Progress Report from July to September 1971 (covering interim examination of exposed specimens after 159 days)

(b) Progress Report from February to June 1972 (covering metallurgical examination of exposed specimens after periods ranging from 159 to 245 days).

(c) Fourth, Fifth, Sixth and Seventh Progress Reports from November 1974 to December 1975 (covering fatigue test results of exposed specimens after 448 days (unprotected) and 688 days (protected).

2. - Final Report on exposed specimens including fatigue tests and metallurgical examination of failures.

Short Brothers and Harland Ltd.

Ref. ERD Report No.226, July 1976.

EXPOSURE TESTS

TABLE 1 ALLOCATION OF STANDARD SPECIMENS COMPARABLE WITH STAGE 1 SPECIMENS — Reference Figure 1

Specimen Type	d/D	Degree of Fit	Number of Specimens and Nature of Protective Treatment
1 C 3/4	3/8	0.8°/o I.F.	3 off each type finish as received i.e. unprotected 3 off each type with standard protective treatment
2 A 5/16	1/4	Push 0.4°/o I.F. 0.8°/o I.F.	
2 C 15/32	3/8	Push 0.4°/o I.F. 0.8°/o I.F.	
2 C 5/8	1/2	Push 0.4°/o I.F. 0.8°/o I.F.	
4 C 9/32	3/8	0.8°/o I.F.	

I.F. Interference Fit

TABLE 2A ALLOCATION OF NON-STANDARD SPECIMENS COMPARABLE WITH SUPPLEMENTARY INVESTIGATION NO.1 SPECIMENS (INTERFERENCE PRE-STRESSED HOLES) — Reference Figure 1

NB All holes initially to Push Fit standard

Specimen Type	d/D	Ball oversize	Number of Specimens and Nature of Protective Treatment
2 B 5/16	1/4	1°/o 4°/o	3 off each type unprotected 3 off each type with standard protective treatment
2 D 15/32	3/8	1°/o 4°/o	
2 D 5/8	1/2	1°/o 4°/o	

TABLE 2B NON-STANDARD SPECIMENS COMPARABLE WITH SUPPLEMENTARY INVESTIGATION No.3 SPECIMENS PRE-LOADED SPECIMENS

Specimen Type	d/D	Pin Fit	Pre-Stress (f_t)	Number of Specimens and Nature of Protective Treatment
4 B 3/16	1/4	Push 0.4°/o I.F. 0.8°/o I.F.	0.75 0.60 0.75 0.60 0.75 0.60	2 off each type unprotected
4 D 9/32	3/8	Push 0.4°/o I.F. 0.8°/o I.F.	0.75 0.60 0.75 0.60 0.75 0.60	2 off each type with Standard Protective Treatment
4 D 3/8	1/2	Push 0.4°/o I.F. 0.8°/o I.F.	0.75 0.60 0.75 0.60 0.75 0.60	

TABLE 2C COMPARABLE WITH SUPPLEMENTARY INVESTIGATION No.7 SPECIMENS PRESS-FORMED RADII

Specimen Type	d/D	Press Form Tool Load	Number of Specimens and Nature of Protective Treatment
2 B 5/16	1/4	4 Tons	2 off each type unprotected
2 D 15/32	3/8	4.5 Tons	2 off each type with Standard Protective Treatment
2 D 5/8	1/2	5 Tons	

TABLE 3 TYPES OF CORROSION ON UNPROTECTED SPECIMENS Reference Figures 2A and 2B and paragraph 5

PLATE		
TYPE	Description	Figure
1	Uniform corrosive attack up to pin	2A
2	Ring of material around pin on both sides relatively unattacked	2B
3	Ring of material around pin on entrance side relatively unattacked	2B

PIN		
TYPE	Description	Figure
1	Uniform rusting of pin	2A
2	Rusting where Cadmium abraded	-
3	Pin relatively free from rust	2B

SUPPLEMENTARY INVESTIGATION No.8

TABLE 4 CORROSION CONDITION OF STANDARD (STAGE 1) UNPROTECTED SPECIMENS AFTER 159 DAYS

Specimen Type	d/D	Degree of Fit	Specimen Identity	Type of Attack*		
				Plate	Pin	
1 C 3/4	3/8	0.8°/o I.F.	1.1.A 1.1.C 1.1.D	2	2	(a)
2 A 5/16	1/4	Push	26.15.E 26.16.C	2	2	
2 A 5/16	1/4	0.4°/o I.F.	25.7.C 29.2.E 29.3.A	2	3 2 2	
2 A 5/16	1/4	0.8°/o I.F.	24.18.Cϕ 24.1.E 24.2.D	3	2	
2 C 15/32	3/8	Push	7.12.C 7.12.D 7.12.E	2 1 2	2 1 2	
2 C 15/32	3/8	0.4°/o I.F.	7.15.D 7.15.E 7.16.A	2	3 2 2	
2 C 15/32	3/8	0.8°/o I.F.	10.6.Aϕ 10.6.B 10.6.D	3	3 2 3	
2 C 5/8	1/2	Push	7.2.C 7.2.D 7.2.E	2	2	
2 C 5/8	1/2	0.4°/o I.F.	5.19.Dϕ 5.19.E 5.20.A	1	1	(b)
2 C 5/8	1/2	0.8°/o I.F.	3.1.C	2	2	
4 C 9/32	3/8	0.8°/o I.F.	13.26.I 13.26.Jϕ 13.27.F	1	1	

(a) Some cases only partial ring around pin on exit side as consequence of cadmium abrasion.

(b) Partial ring around pin on entrance side where some cadmium intact.

ϕ Subjected to metallurgical examination.

* See Table 3 for key to type numbers.

SUPPLEMENTARY INVESTIGATION No.8

TABLE 5 CORROSION CONDITION OF NON-STANDARD SUPPLEMENTARY INVESTIGATION No.1 UNPROTECTED SPECIMENS AFTER 159 DAYS

NB All holes initially to Push Fit standard

Specimen Type	d/D	Ball Oversize	Specimen Identity	Type of Attack* Plate	Pin
2 B 5/16	1/4	1°/o	23.1.E 23.15.A 23.15.B	2	2
2 B 5/16	1/4	4°/o	24.7.Eϕ 24.8.D 24.9.E	2	3
2 D 15/32	3/8	1°/o	7.16.B 7.16.C 7.16.D	2	1
2 D 15/32	3/8	4°/o	9.13.A 9.13.B 9.13.Cϕ	2	2 1 1
2 D 5/8	1/2	1°/o	6.3.E 6.4.A 6.4.B	2	1
2 D 5/8	1/2	4°/o	6.8.E 3.2.B 3.2.C	2	3

ϕ Subjected to Metallurgical examination

* See Table 3 for key to type numbers

SUPPLEMENTARY INVESTIGATION No.8

TABLE 6 CORROSION CONDITION OF NON-STANDARD SUPPLEMENTARY INVESTIGATION No.3 UNPROTECTED SPECIMENS AFTER 159 DAYS

Specimen Type	d/D	Pin Fit	Pre-stress (f_t)	Specimen Identity	Type of Attack* Plate	Pin	
4 B 3/16	1/4	Push	0.75	12.12.0 12.12.I	1	3	
			0.60	12.11.N 12.11.M	1	3	
		0.4°/o I.F.	0.75	12.1.E 12.1.F	1	3	
			0.60	12.1.A 12.1.B	2	3	(a)
		0.8°/o I.F.	0.75	12.6.B 12.6.C	1	2	(b)
			0.60	12.2.D 12.3.D	2	2	(a)
4 D 9/32	3/8	Push	0.75	21.2.G 21.2.M	1	3	
			0.60	21.2.E 21.2.F	2	3	
		0.4°/o I.F.	0.75	21.3.I 21.14.D	1 2	2	(c)
			0.60	21.3.C 21.3.D	2	2	
		0.8°/o I.F.	0.75	21.3.Mϕ 21.3.N	2	2 3	
			0.60	21.2.N 21.3.J	2	3	
4 D 3/8	1/2	Push	0.75	23.6.A 23.6.C	2	1 3	
			0.60	23.5.J 23.5.L	2	1	
		0.4°/o I.F.	0.75	22.11.G 22.11.I	2	2	
			0.60	22.11.M 22.11.N	2	3 2	
		0.8°/o I.F.	0.75	22.12.Nϕ 22.12.O	2	2	
			0.60	22.12.Eϕ 22.12.I	2	2	

(a) Partial rings around pin where pin contacts plate, due to bearing failure which occurred in all 4 B 3/16 specimens

(b) Partial ring around pin on exit side where plate contacted pin.

(c) 0.90 f_t pre-stress applied in error. Ring around pin on exit side.

ϕ Subjected to metallurgical examination

* See Table 3 for key to type numbers.

TABLE 7 CORROSION CONDITION OF NON-STANDARD SUPPLEMENTARY INVESTIGATION No.7 UNPROTECTED SPECIMENS AFTER 159 DAYS

Specimen Type	d/D	Press Form Tool Load	Specimen Identity	Type of Attack*		
				Plate	Pin	
2 B 5/16	1/4	4 Tons	28.9.Bϕ 27.9.C	1	1	
2 D 15/32	3/8	4.5 Tons	14.3.E 14.4.B	2	1	(a)
2 D 5/8	1/2	5 Tons	6.16.C 6.16.D	2	2	

(a) Only partial ring around pin on exit side

ϕ Subjected to metallurgical examination

* See Table 3 for key to type numbers

TABLE 8 SPECIMENS SELECTED FOR METALLURGICAL EXAMINATION Reference paragraph 6

S.I. or Stage 1	Specimen Type	d/D	Specimen Identity	Reason for Selection	Number of Days Exposure
Stage 1 Standard Specimen	2 A 5/16 4 C 9/32 2 C 15/32	1/4 3/8 3/8	24.18.C 13.26.J 10.6.A	0.8^{o}/o I.F. and corrosion extending to the edge of hole	159
	2 C 5/8	1/2	5.19.D	As above but 0.4^{o}/o I.F.	245
S.I. No.1 Pre-stress Hole	2 B 5/16 2 D 15/32	1/4 3/8	24.7.E 9.13.C	4^{o}/o oversize ball used for pre-stressing	159
S.I. No.3	4 D 9/32 4 D 3/8	3/8 1/2	21.3.M 22.12.N	0.75 f_t Pre-Loading combined with 0.8^{o}/o I.F.	159
Specimen Pre-Loading	4 D 3/8	1/2	22.12.E	Cut after 22.12.N examined. Less extreme case (0.60 f_t) to see if cracking persisted.	238
S.I. No.7 Press-formed Radii	2 B 5/16	1/4	28.9.B	Typical Specimen	159

SUPPLEMENTARY INVESTIGATION No.8

TABLE 9A FATIGUE ENDURANCES OF STANDARD SPECIMENS COMPARABLE WITH STAGE 1 TEST RESULTS

Reference Figures 6 to 16

LARGE SPECIMENS Type 1 C 3/4 d/D = 3/8 Pin Unloaded

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
0.8°/o I.F.	No	1.1.A ✓	50	22.5	147 000	5.167
	Yes	1.1.E ✓		22.5	281 000	5.438
	No	1.1.C		12.5	2 304 000	6.363
	Yes	1.2.B		12.5	5 753 000	6.759
	No	1.1.D		7.5	10 000 000U	7.000U
	Yes	1.2.E		7.5	10 000 000U	7.000U

TABLE 9B MEDIUM SPECIMENS Type 2 A 5/16 d/D = 1/4 Pin Unloaded

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
Push	No	26.15.E ✓	25	22.5	60 000	4.777
	Yes	30.3.D ✓		22.5	76 000	4.880
	Yes	30.4.B ✓		12.5	201 000	5.302
	No	26.16.C ✗		7.5	485 000	5.685
	Yes	30.4.C		7.5	643 000	5.807
0.4°/o I.F.	No	25.7.C ✓	50	22.5	41 000	4.612
	Yes	29.3.B ✓		22.5	85 900	4.933
	No	29.2.E ✓		12.5	85 000	4.929
	Yes	29.4.A		12.5	218 000	5.338
	No	29.3.A		7.5	439 000	5.642
	Yes	29.4.B		7.5	705 000	5.848
0.8°/o I.F.	No	24.1.E ✗	50	22.5	56 000	4.748
	Yes	24.3.E ✓		22.5	86 000	4.934
	Yes	24.4.D		12.5	490 000	5.690
	No	24.2.D ✗		7.5	10 000 000U	7.000U
	Yes	24.5.D		7.5	10 000 000U	7.000U

U denotes specimen unfailed

✓ Examined by binocular microscope < x 60

✗ Subjected to micro-examination x 63 or x 125

Continued..

TABLE 9C MEDIUM SPECIMENS - Type 2 C 15/32 d/D = 3/8 Pin Unloaded

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	Stress Levels Percentage f_t $\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
Push	No	7.12.C ✓	25	22.5	155 000	5.189
	Yes	7.15.A ✓		22.5	120 000	5.079
	No	7.12.D		12.5	173 000	5.238
	Yes	7.15.B		12.5	203 000	5.308
	No	7.12.E ✓		7.5	279 000	5.445
	Yes	7.15.C ✓		7.5	483 000	5.683
0.4^o/o I.F.	No	7.15.D	50	22.5	77 000	4.886
	Yes	10.5.C		22.5	46 000	4.662
	No	7.15.E		12.5	100 000	5.000
	Yes	10.5.D		12.5	154 000	5.186
	No	7.16.A		7.5	514 000	5.710
	Yes	10.5.E		7.5	no result +	-
0.8^o/o I.F.	No	10.6.B ✓	50	22.5	75 000	4.875
	Yes	10.6.E ✓		22.5	50 000	4.699
	Yes	10.7.A		12.5	206 000	5.314
	No	10.6.D ✓		7.5	464 000	5.665
	Yes	10.7.B		7.5	10 000 000U	7.000U

TABLE 9D MEDIUM SPECIMENS - Type 2 C 5/8 d/D = 1/2 Pin Unloaded

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	Stress Levels Percentage f_t $\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
Push	No	7.2.C ✓	25	22.5	no result +	-
	Yes	7.3.A		22.5	no result +	-
	No	7.2.D		12.5	275 000	5.438
	Yes	7.3.D		12.5	10 000 000U	7.000U
	No	7.2.E		7.5	1 693 000	6.228
	Yes	7.3.C		7.5	10 000 000U	7.000U
0.4^o/o I.F.	No	5.19.E	50	22.5	36 000	4.556
	Yes	6.20.C		22.5	100 000	5.000
	Yes	5.20.D		12.5	318 000	5.501
	No	5.20.A		7.5	1 455 000	6.161
	Yes	5.20.E		7.5	10 000 000U	7.000U
0.8^o/o I.F.	No	3.1.C ✓	50	22.5	52 000	4.715
	Yes	3.1.D ✓		22.5	78 000	4.891
	Yes	3.2.A		7.5	10 000 000U	7.000U

U denotes specimen unfailed
\+ No result signifies failure of Vibrophore machine to trip at specimen failure
✓ Examined by binocular microscope <x60

SUPPLEMENTARY INVESTIGATION No.8

TABLE 9E SMALL SPECIMENS Type 4 C 9/32 d/D = 3/8 Pin Unloaded

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
0.8°/o I.F.	No	13.26.J ✓		22.5	54 000	4.732
	Yes	14.14.C ✓		22.5	47 000	4.671
	Yes	14.14.D	50	12.5	3 496 000	6.543
	No	13.27.F ✗		7.5	10 000 000U	7.000U
	Yes	14.14.E		7.5	10 000 000U	7.000U

U denotes specimen unfailed

TABLE 10A FATIGUE ENDURANCES OF NON-STANDARD SPECIMENS Reference Figures 17,18 and 19
COMPARABLE WITH SUPPLEMENTARY INVESTIGATION No.1

Note Interference Pre-stressed Holes
All holes initially to Push Fit Standard
MEDIUM SPECIMENS Type 2 B 5/16 d/D = 1/4 Pin Loaded

Ball Oversize	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
	No	23.1.E		22.5	9 000	3.955
	Yes	23.15.C		22.5	14 500	4.160
1°/o	No	23.15.A	25	12.5	35 000	4.544
	Yes	23.15.D		12.5	40 000	4.601
	No	23.15.B		7.5	51 500	4.711
	Yes	23.15.E		7.5	61 000	4.785
	No	24.8.D ✓		22.5	10 000	4.000
	Yes	24.15.E ✓		22.5	15 000	4.175
4°/o	Yes	25.1.D	25	12.5	127 000	5.103
	No	24.9.E ✓		7.5	254 000	5.404
	Yes	25.3.E ✓		7.5	128 000	5.107

TABLE 10B MEDIUM SPECIMENS Type 2 D 15/32 d/D = 3/8 Pin Loaded

Ball Oversize	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
	No	7.16.B		22.5	19 000	4.278
1°/o	Yes	7.16.E		22.5	24 000	4.380
	No	7.16.C	25	12.5	177 000	5.247
	Yes	7.17.A		12.5	177 000	5.247
	No	9.13.A ✓		22.5	30 000	4.477
	Yes	9.12.D ✓		22.5	191 000	5.280
4°/o	Yes	9.13.E	25	12.5	247 000	5.392
	No	9.13.B ✗		7.5	713 000	5.852
	Yes	9.14.A ✓		7.5	1 874 000	6.272

✓ Examined by binocular microscope < x 60
✗ Subjected to micro-examination x 63 or x 125

SUPPLEMENTARY INVESTIGATION No.8

TABLE 10C MEDIUM SPECIMENS Type 2 D 5/8 d/D = 1/2 Pin Loaded

Ball Oversize	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
$1^o/o$	No	6.3.E	25	22.5	32 000	4.505
	Yes	6.4.D		22.5	64 000	4.805
	No	6.4.A		12.5	50 000	4.699
	Yes	6.4.E		12.5	90 000	4.954
	No	6.4.B		7.5	327 000	5.514
	Yes	6.5.A		7.5	549 000	5.738
$4^o/o$	No	3.2.B ✓	25	22.5	25 000	4.398
	Yes	3.2.D ✓		22.5	40 000	4.601
	Yes	3.3.A		12.5	111 000	5.045
	No	3.2.C ✓		7.5	319 000	5.503
	Yes	3.3.C ✓		7.5	516 000	5.712

TABLE 11A FATIGUE ENDURANCES FOR NON-STANDARD SPECIMENS COMPARABLE WITH SUPPLEMENTARY INVESTIGATION No.3 Reference Figures 20 to 28

Pre-Loaded Specimens

SMALL SPECIMENS Type 4 B 3/16 d/D = 1/4 Pin Loaded

0.75 f_t Pre-Stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
Push	No	12.12.O ✓	25	22.5	12 000	4.079
	Yes	12.12.H ✓		22.5	33 000	4.518
	No	12.12.I ✓		7.5	148 000	5.170
	Yes	12.12.G ✓		7.5	757 000	5.878
$0.4^o/o$I.F.	No	12.1.E ✓	25	22.5	13 000	4.114
	Yes	12.1.M ✓		22.5	21 000	4.322
	No	12.1.F ✓		7.5	428 000	5.630
	Yes	12.1.N ✓		7.5	666 000	5.822
$0.8^o/o$I.F.	No	12.6.B	25	22.5	16 000	4.204
	Yes	12.7.J		22.5	19 000	4.278
	No	12.6.C		7.5	190 000	5.278
	Yes	12.7.M		7.5	372 000	5.570

✓ Examined by binocular microscope < x 60

SUPPLEMENTARY INVESTIGATION NO.8

TABLE 11B SMALL SPECIMENS Type 4 B 3/16 d/D = 1/4 Pin Loaded

$0.60\ f_t$ Pre-Stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	Stress Levels Percentage f_t $\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
Push	No	12.11.N ✗	25	22.5	16 000	4.203
	Yes	12.11.L ✓		22.5	26 000P	4.415P
	No	12.11.M ✓		7.5	428 000	5.631
	Yes	12.11.K ✓		7.5	527 000	5.721
0.4°/oI.F.	No	12.1.A ✓	25	22.5	14 000	4.415
	Yes	12.1.C ✓		22.5	24 000	4.380
	No	12.1.B ✓		7.5	298 000	5.474
	Yes	12.1.D ✓		7.5	576 000	5.759
0.8°/oI.F.	No	12.2.D	25	22.5	14 000	4.146
	Yes	12.14.G ✓		22.5	17 500	4.243
	No	12.3.D ✓		7.5	277 000	5.442
	Yes	12.4.H ✓		7.5	505 000	5.704

P denotes pin failure

TABLE 11C SMALL SPECIMENS Type 4 D 9/32 d/D = 3/8 Pin Loaded

$0.75\ f_t$ Pre-Stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	Stress Levels Percentage f_t $\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
Push	No	21.2.G ✓	25	22.5	17 000	4.230
	Yes	21.3.A ✗		22.5	37 000	4.568
	No	21.2.M ✓		7.5	547 000	5.737
	Yes	21.3.B		7.5	10 000 000U	7.000U
0.4°/oI.F.	No	21.3.I	25	22.5	13 500	4.130
	Yes	21.14.E		22.5	47 000	4.661
	No	21.14.D		7.5	246 000	5.390
	Yes	21.14.F		7.5	653 000	5.815
0.8°/oI.F.	No	21.3.N ✓	25	22.5	35 000	4.543
	Yes	21.3.O ✓		22.5	85 000	4.930
	Yes	21.4.A		7.5	10 000 000U	7.000U

U Denotes specimen unfailed

✓ Examined by binocular microscope < x 60

✗ Subjected to micro-examination x 63 or x 125

SUPPLEMENTARY INVESTIGATION No.8

TABLE 11D SMALL SPECIMENS - Type 4 D 9/32 $d/D = 3/8$ Pin Loaded

$0.60\ f_t$ Pre-stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	$\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
	No	21.2.E ✓		22.5	32 000	4.505
Push	Yes	21.2.L ✓	25	22.5	40 000	4.601
	No	21.2.F ✓		7.5	993 000	5.996
	Yes	21.2.I ✓		7.5	10 000 000U	7.000U
	No	21.3.C		22.5	13 000	4.113
0.4^o/oI.F.	Yes	21.3.E	25	22.5	70 000	4.845
	Yes	21.3.G		7.5	10 000 000U	7.000U
	No	21.2.N ✓		22.5	202 000	5.305
0.8^o/oI.F.	Yes	21.3.K ✓	25	22.5	J	-
	No	21.3.J ✗		7.5	10 000 000U	7.000U
	Yes	21.3.L		7.5	10 000 000U	7.000U

✓ Examined by binocular microscope < x 60
✗ Subjected to micro-examination x 63 or x 125

TABLE 11E SMALL SPECIMENS Type 4 D 3/8 $d/D = 1/2$ Pin Loaded

$0.75\ f_t$ Pre-stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	$\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
	No	23.6.A		22.5	25 000	4.398
Push	Yes	23.6.G	25	22.5	2 656 000	6.425
	No	23.6.C		7.5	279 000	5.445
	No	22.11.G		22.5	64 000	4.806
	Yes	22.12.A		22.5	646 000	5.810
0.4^o/oI.F.	No	22.11.I	25	7.5	1 060 000	6.025
	Yes	22.12.B		7.5	10 000 000U	7.000U
	No	22.12.O		22.5	J	-
0.8^o/oI.F.	Yes	22.13.B	25	22.5	406 000	5.608
	Yes	22.13.F		7.5	10 000 000U	7.000U

U denotes specimen unfailed
J denotes failed at Jaws

SUPPLEMENTARY INVESTIGATION No.8

TABLE 11F SMALL SPECIMENS Type 4 D 3/8 d/D = 1/2 Pin Loaded

$0.60\ f_t$ Pre-Stress

Pin Fit	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
Push	No	23.5.J	25	22.5	20 000	4.301
	Yes	23.6.D		22.5	467 000	5.670
	No	23.5.L		7.5	262 000	5.419
	Yes	23.6.B		7.5	10 000 000U	7.000U
0.4°/oI.F.	No	22.11.M	25	22.5	79 000	4.897
	Yes	22.11.J		22.5	1 689 000	6.227
	No	22.11.N		7.5	10 000 000U	7.000U
	Yes	22.11.L		7.5	10 000 000U	7.000U
0.8°/oI.F.	No	22.12.I	25	22.5	J	-
	Yes	22.12.J		22.5	607 000	5.782
	Yes	22.12.M		7.5	10 000 000U	7.000U

J denotes failure at Jaws

TABLE 12A FATIGUE ENDURANCES FOR NON-STANDARD SPECIMENS Reference Figures 29 to 31
COMPARABLE WITH SUPPLEMENTARY INVESTIGATION No.7
Press-Formed Radii
MEDIUM SPECIMENS Type 2 B 5/16 d/D = 1/4 Pin Loaded

Press* Form Load	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
4 Tons	No	28.9.C ✗	25	22.5	18 000	4.255
	Yes	28.9.D √		22.5	31 000	4.490
	Yes	28.9.E		7.5	10 000 000U	7.000U

√ Examined by binocular microscope < x 60

TABLE 12B MEDIUM SPECIMENS Type 2 D 15/32 d/D = 3/8 Pin Loaded

Press* Form Load	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure
			S_m	$\pm S_a$		
4.5 Tons	No	14.3.E	25	22.5	#	#
	Yes	14.4.D ✗		22.5	187 000	5.271
	No	14.4.B		7.5	10 000 000U	7.000U
	Yes	14.5.B		7.5	10 000 000U	7.000U

U denotes specimen unfailed
* Hole initially to push fit standard
# Signifies that specimen slipped in the jaws during testing and this produced misalignment
✗ Subjected to micro-examination x 63 or x 125

TABLE 12C MEDIUM SPECIMENS Type 2 D 5/8 d/D = 1/2 Pin Loaded

Press* Form Load	Protection (Yes or No)	Specimen Identity	Stress Levels Percentage f_t S_m	$\pm S_a$	Cycles to Failure	Logarithm Cycles to Failure
5.0 Tons	No	6.16.C	25	22.5	+	+
	Yes	6.16.E		22.5	10 000 000U	7.000U
	No	6.16.D		7.5	10 000 000U	7.000U
	Yes	6.17.A		7.5	10 000 000U	7.000U

U denotes specimen unfailed

* Hole initially to push fit standard

\+ Signifies that specimen slipped in the jaws during testing and this produced misalignment

TABLE 13 EFFECT ON ENDURANCE OF OMISSION OF PROTECTIVE TREATMENT AND COMPARISON WITH STAGE 1 Reference Table 9 and Figures 6 to 16

Standard Specimens Pin Unloaded

Specimen Type	d/D	S_m/f_t	Pin Fit	Endurance Ratios* Unprotected / Protected	Protected / Stage 1
1 C 3/4	3/8	0.50	0.8^o/oI.F.	0.5 to 0.4	No Stage 1 data
2 A 5/16	1/4	0.25	Push	0.8 to 0.7	1.0 to 0.2
		0.50	0.4^o/oI.F.	0.5 to 0.6	3.0 to 2.0
		0.50	0.8^o/oI.F.	0.6 to 0.6	1.0 to 1.0
2 C 15/32	3/8	0.25	Push	1.3 to 0.6	1.7 to 0.1
		0.50	0.4^o/oI.F.	1.2 to 0.7	No Stage 1 data
		0.50	0.8^o/oI.F.	1.5 to 0.1	available
2 C 5/8	1/2	0.25	Push	0.2	No Stage 1 data
		0.50	0.4^o/oI.F.	0.4 to 0.2	1.0 to 0.3
		0.50	0.8^o/oI.F.	0.7 to ?	No Stage 1 data
4 C 9/32	3/8	0.50	0.8^o/oI.F.	1.2 to ?	No Stage 1 data

* First ratio refers to high S_a and second ratio to low S_a

? signifies insufficient data to enable endurance ratio to be quoted

TABLE 14 EFFECT ON ENDURANCE OF OMISSION OF PROTECTIVE TREATMENT AND COMPARISON WITH SUPPLEMETARY INVESTIGATION No.1 Reference Table 10 and and Figures 17 to 19

Non-Standard Specimens Interference Pre-Stressed Holes Pin Loaded

Specimen Type	d/D	S_m/f_t	Ball Oversize	Endurance Ratios* Unprotected / Protected	Protected / S.I.No.1
2 B 5/16	1/4	0.25	1^o/o	0.6 to 0.8	1.3 to 0.2
			4^o/o	0.7 to 1.2	1.5 to 1.0
2 D 15/32	3/8	0.25	1^o/o	0.8 to 1.2	1.8 to 1.2
			4^o/o	0.2 to 0.4	3.8 to 0.8
2 D 5/8	1/2	0.25	1^o/o	0.6 to 0.5	1.6 to 0.1
			4^o/o	0.6 to 0.6	1.8 to 0.1

* First ratio refers to high S_a and second ratio to low S_a

TABLE 15 SUPPLEMENTARY INVESTIGATION No.8
EFFECT ON ENDURANCE OF OMISSION OF PROTECTIVE TREATMENT AND COMPARISON WITH SUPPLEMENTARY INVESTIGATION No.3

Reference Table 11 and Figures 20 to 28

Non-Standard Pre-loaded Specimens   Pin Loaded

$S_m/f_t = 0.25$ throughout

Specimen Identity	d/D	Pre-Stress (f_t)	Hole Fit Push or I.F.	Endurance Ratio* Unprotected / Protected	Endurance Ratio* Protected / S.I. No.3
4 B 3/16	1/4	0.75	Push	0.4 to 0.2	0.6 to 0.05
			0.4°/o	0.6 to 0.6	0.4 to 0.05
			0.8°/o	0.8 to 0.5	0.6 to 0.02
		0.60	Push	0.6 to 0.8	1.2 to 0.1
			0.4°/o	0.6 to 0.5	0.8 to 0.05
			0.8°/o	0.8 to 0.5	0.6 to 0.07
4 D 9/32	3/8	0.75	Push	0.5 to 0.05	0.8 to 1.0
			0.4°/o	0.3 to 0.4	1.0 to 0.03
			0.8°/o	0.4 to ?	1.1 to 0.3
		0.60	Push	0.8 to 0.08	2.5 to 5.0
			0.4°/o	0.2 to ?	1.4 to 7.0
			0.8°/o	?	?
4 D 3/8	1/2	0.75	Push	0.1 to ?	90 to ?
			0.4°/o	0.1 to 0.1	1.5 to 0.7
			0.8°/o	?	25 to ?
		0.60	Push	0.4 to 0.03	1.7 to 35
			0.4°/o	0.1 to 0.3	2.2 to ?
			0.8°/o	?	21 to ?

TABLE 16 EFFECT ON ENDURANCE OF OMISSION OF PROTECTIVE TREATMENT AND COMPARISON WITH SUPPLEMENTARY INVESTIGATION No.7

Reference Table 12 and Figures 29 to 31

Non-Standard Specimens   Press-formed Radii   Pin Loaded

$S_m/f_t = 0.25$ throughout

Specimen Identity	d/D	Press-form Load (Tons)	Endurance Ratio* Unprotected / Protected	Endurance Ratio* Protected / S.I.No.7
2 B 5/16	1/4	4.0	0.6 to ?	2.7 to 2.0
2 D 15/32	3/8	4.5	?	7.5 to 33
2 D 5/8	1/2	5.0	?	75 to ?

* First ratio refers to high S_a and second ratio to low S_a

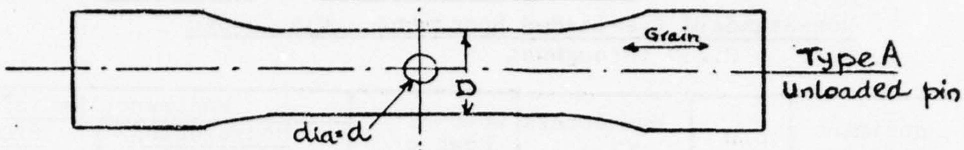
? Signifies insufficient data to enable endurance ratio to be quoted.

S.I. Nº 9 – EXPOSURE TESTS

FIGURE 1 SPECIMEN TYPES

PLATES Drawn for Medium Size – Scale 1/2 (other sizes approx'ly prop'l to width 'D')

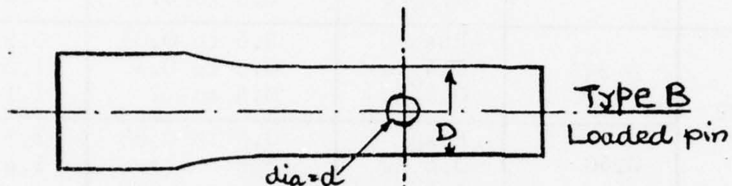
B.S.1.71 – f_t = 69,400 lb/in², 'AS ROLLED' SURFACE



Standard Specimens

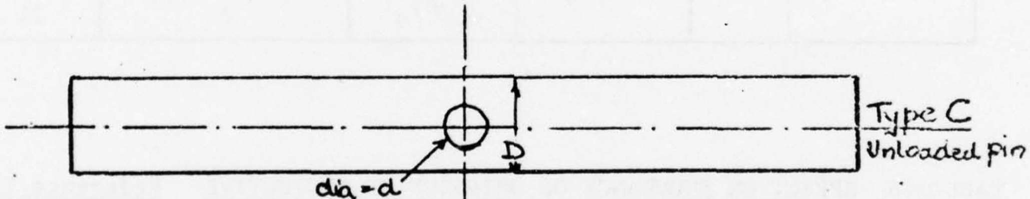
As Stage 1, medium (prefix 2) – 18 off

Specimen Size	width D
Large	2"
Medium	1¼"
Small	¾"



Non-Standard Specimens

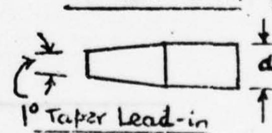
As S.I. Nº1, medium (prefix 2) – 12 off
As S.I. Nº3, small (prefix 4) – 24 off
As S.I. Nº7, medium (prefix 2) – 4 off

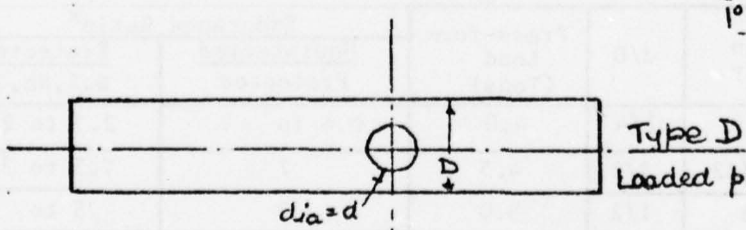


Standard Specimens

As Stage 1, Large (prefix 1) – 6 off
As Stage 1, medium (prefix 2) – 36 off
As Stage 1, small (prefix 4) – 6 off

PIN B.S. S94 Cadmium plated





Non-Standard Specimens

As S.I. Nº1, medium, (prefix 2) – 24 off
As S.I. Nº3, small (prefix 4) – 48 off
As S.I. Nº7, medium (prefix 2) – 8 off

Note Types A & B were used for pin diameters which were small relative to specimen width D.

Types C & D were used for pin diameters which were large relative to specimen width D.

FIGURE 2 ILLUSTRATIONS OF CORROSION ON UNPROTECTED SPECIMENS

(VISUAL)

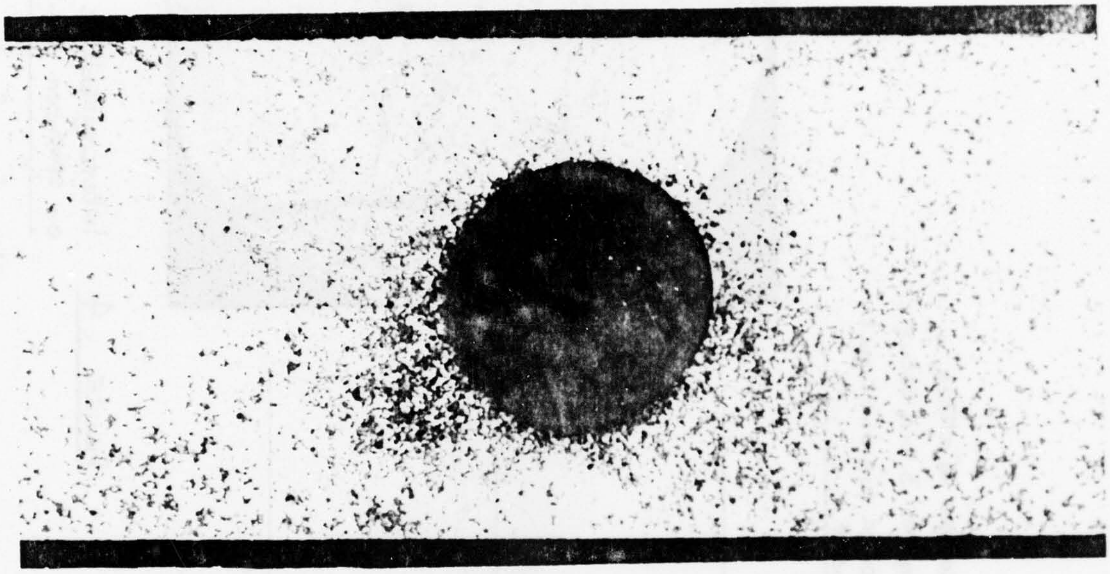


FIG. 2A - Uniform Attack up to pin (specimen 5.19.D)

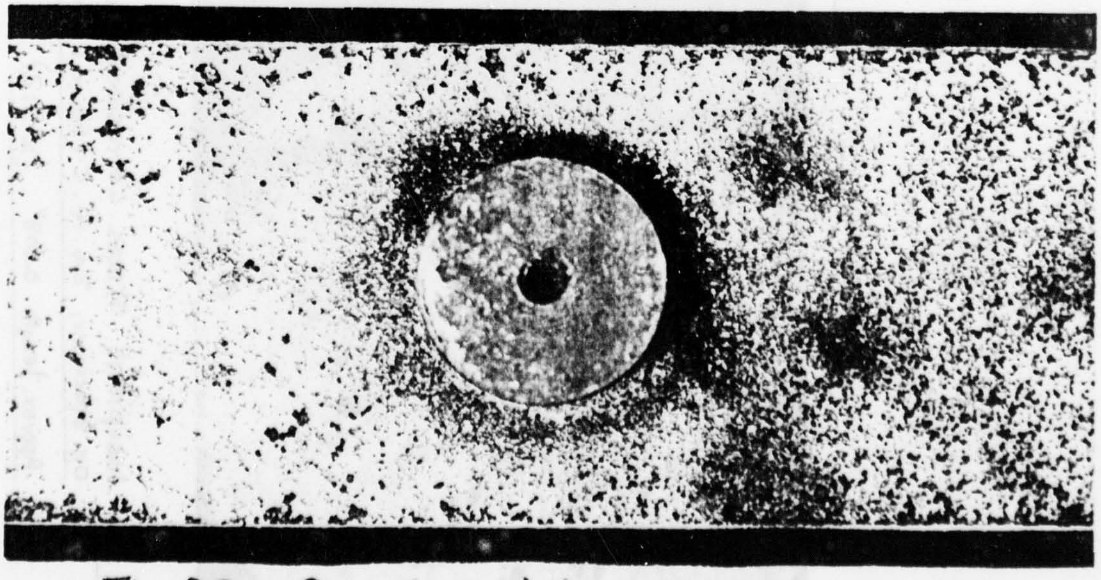


FIG. 2B.- Ring of relatively unattacked material around pin
Also Pin relatively free from rust (Specimen 7.2.E)

S.I. Nº 8 - EXPOSURE TESTS

MICRO- PHOTOGRAPHS

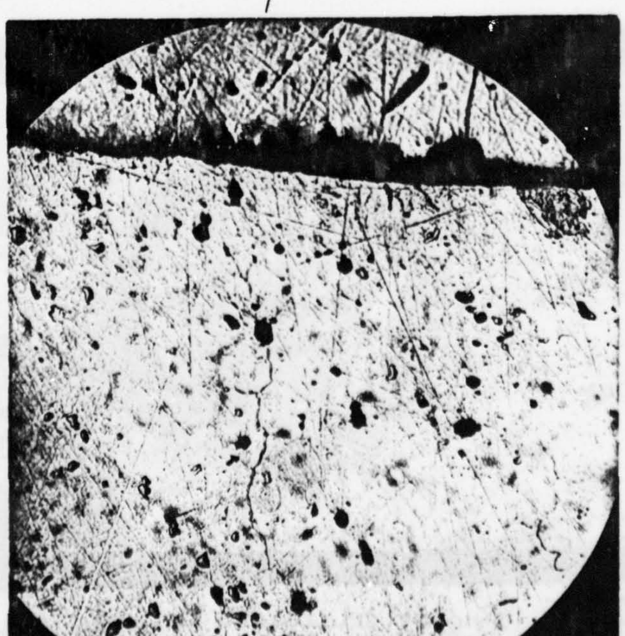
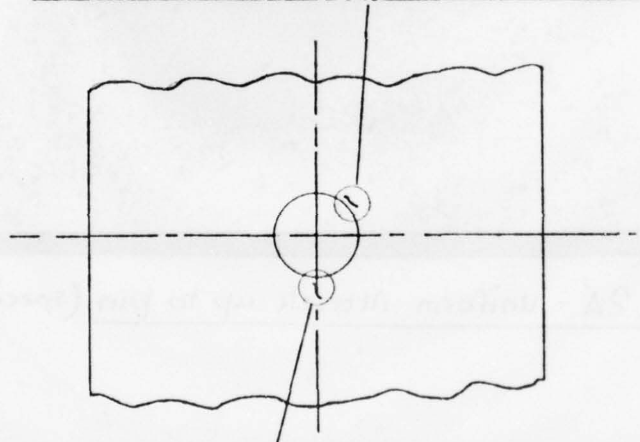


FIGURE 3. Incipient stress corrosion cracking on specimen 24.18.C (Stage 1 type)

Approx. length 0.008" (x 312)

Intermittent cases of attack typified by Figures 3 & 4 occur completely around pin on Stage 1 type specimens.



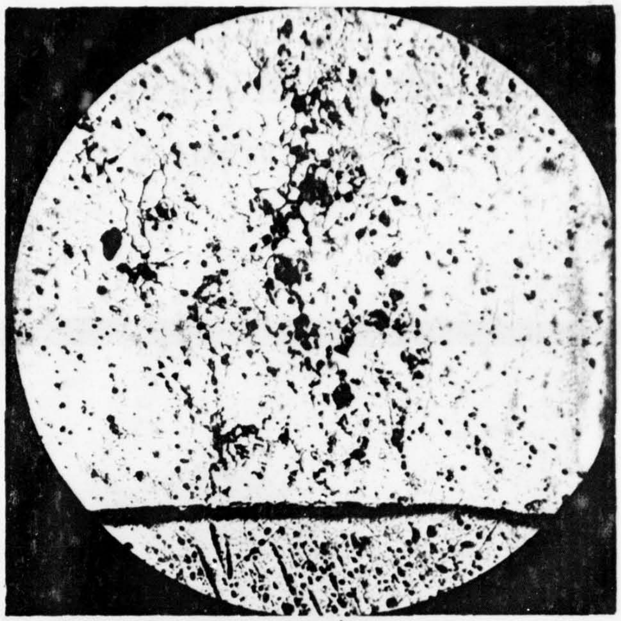


FIGURE 4. Intercrystalline corrosion and pitting on specimen 24.18.C (Stage 1 type)

Dimensions of network $\begin{cases} 0.022'' \text{ Radially} \\ 0.019'' \text{ Circumferentially} \end{cases}$

(x 125)

S.I. N° 8 - EXPOSURE TESTS

MICRO-PHOTOGRAPHS

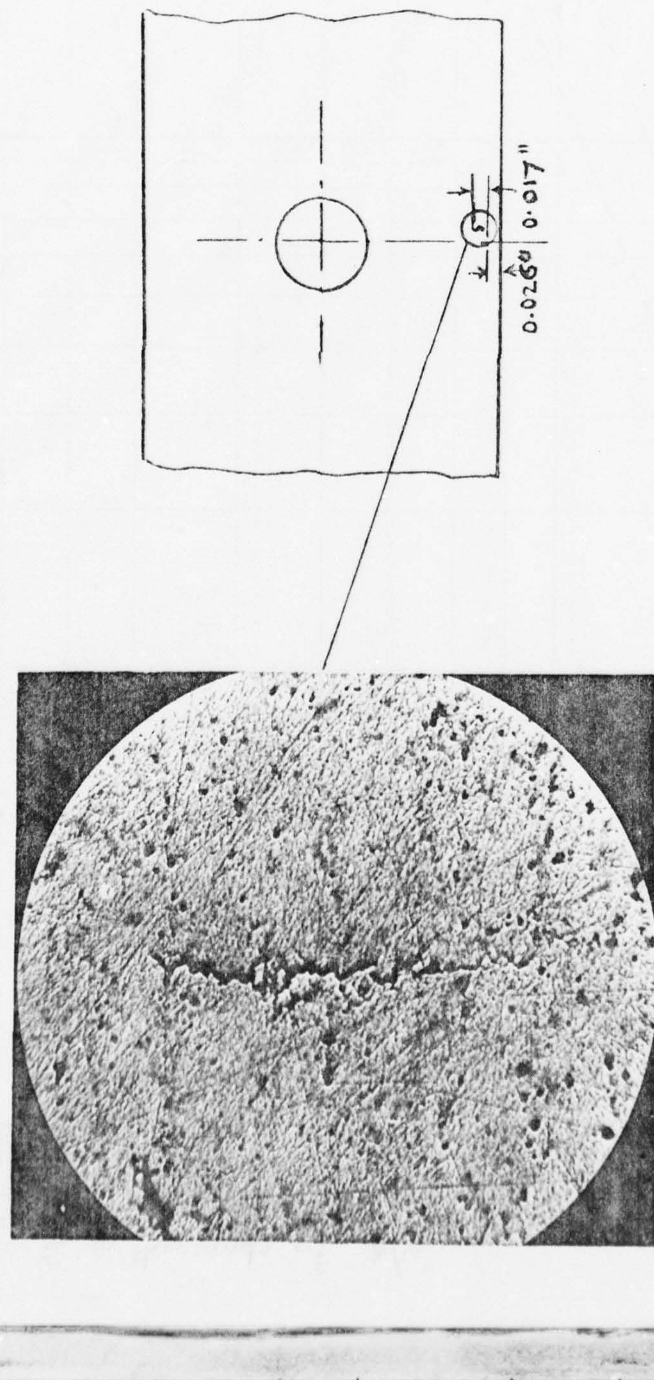


FIGURE 5 Stress corrosion cracking on Specimen 22.12.N (S.I. N° 3 type)

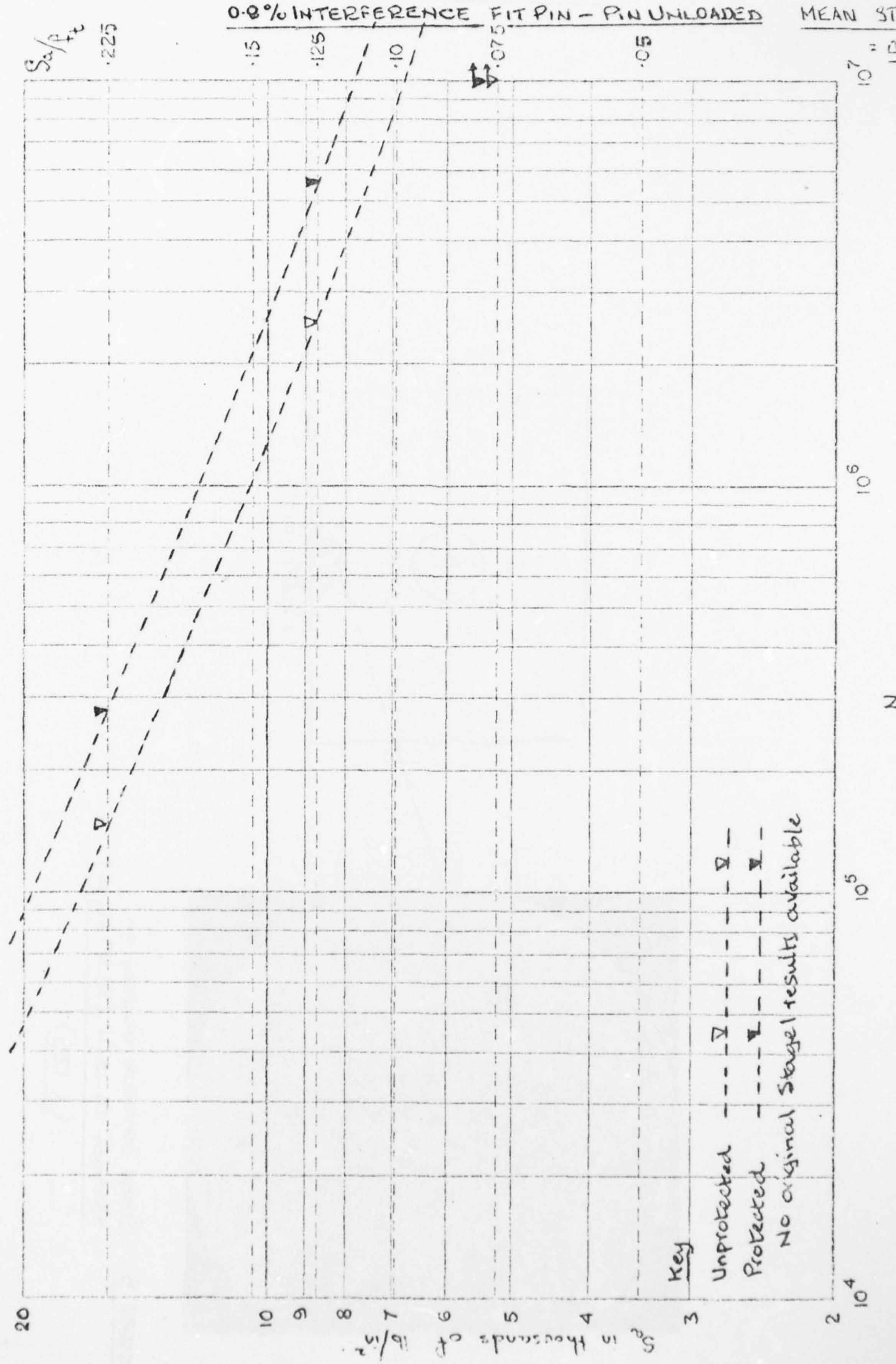
(X 125)

S.I. N° 8 - EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 6 LARGE SIZE, TYPE 1C 3/4, - $d/D = 3/8$ Ref: TABLE 9A

0.8% INTERFERENCE FIT PIN - PIN UNLOADED MEAN STRESS $= 0.50 f_t$

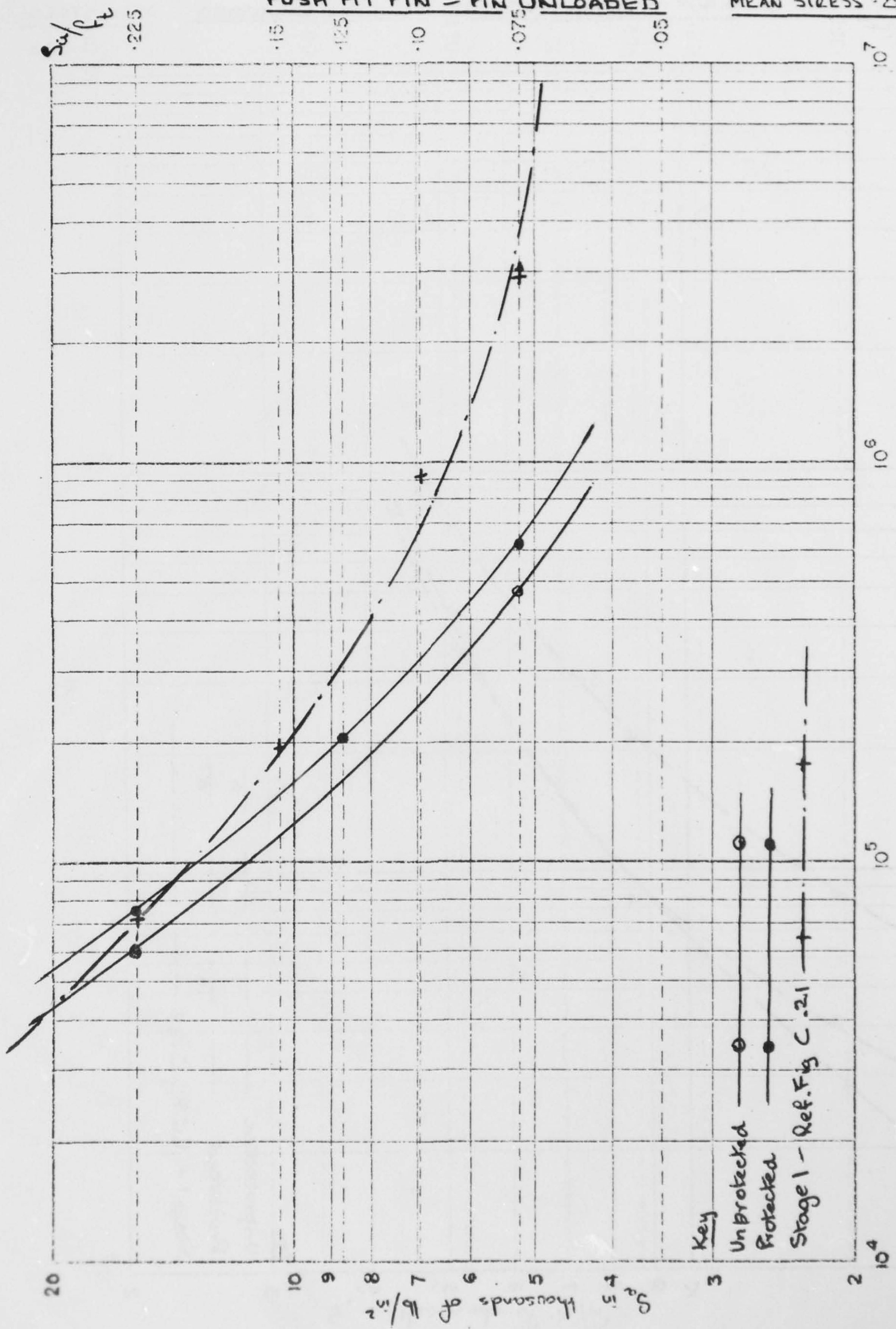


S.I. Nº 8 - EXPOSURE TESTS

ENDURANCES OF STAGE 1 TYPE SPECIMENS

FIGURE 7 MEDIUM SIZE, TYPE 2A 5/16 - d/D = 1/4 Ref. TABLE 9

PUSH FIT PIN - PIN UNLOADED MEAN STRESS = 0·25 f_t

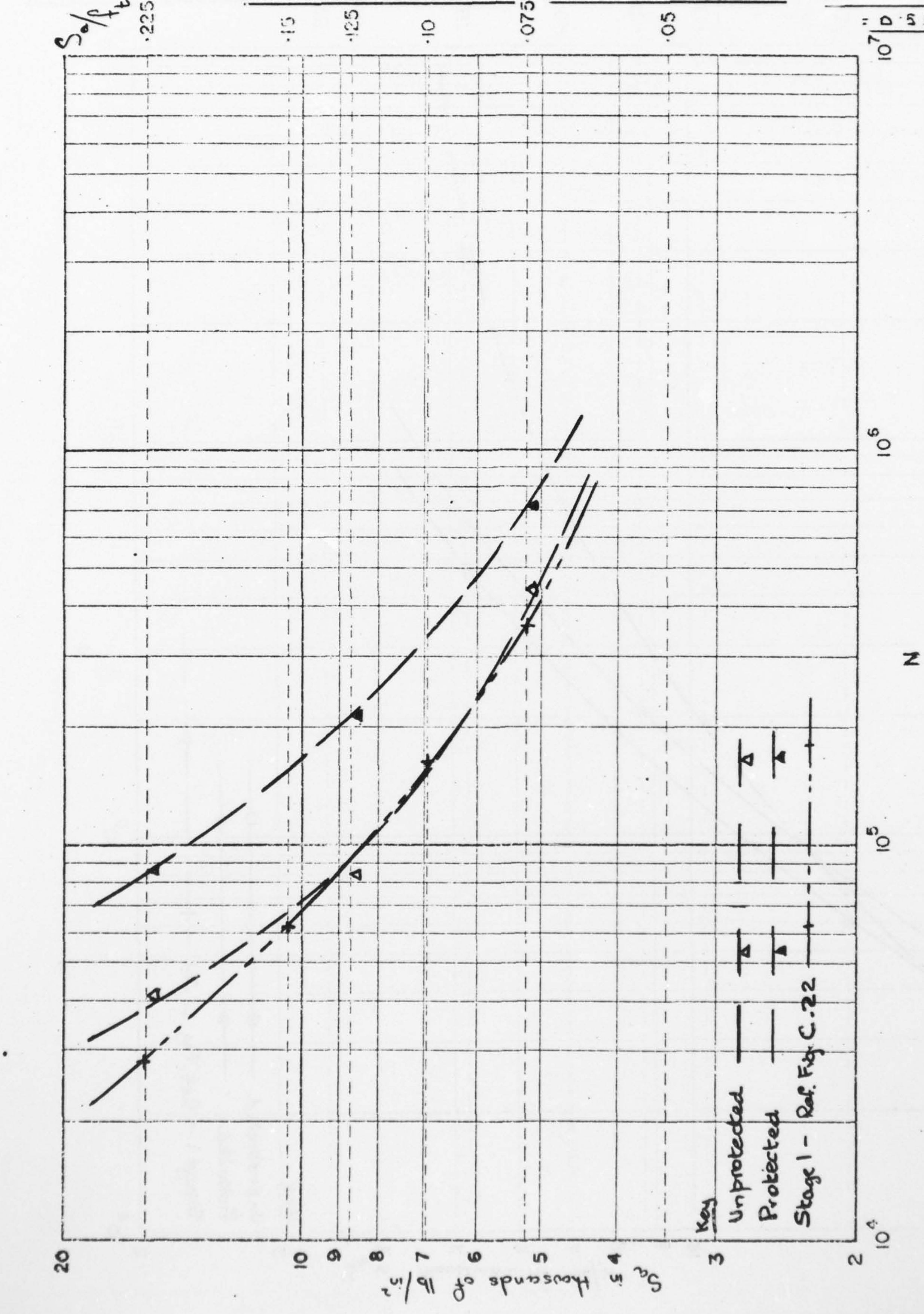


S.I. No 8 - EXPOSURE TESTS

ENDURANCES OF STAGE 1 TYPE SPECIMENS

FIGURE 8 MEDIUM SIZE, TYPE 2A 5/16 - $d/D = 1/4$ Ref: TABLE 9B

0.4% INTERFERENCE FIT PIN - PIN UNLOADED MEAN STRESS $= 0.5 f_t$



S.I. N° 8 – EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

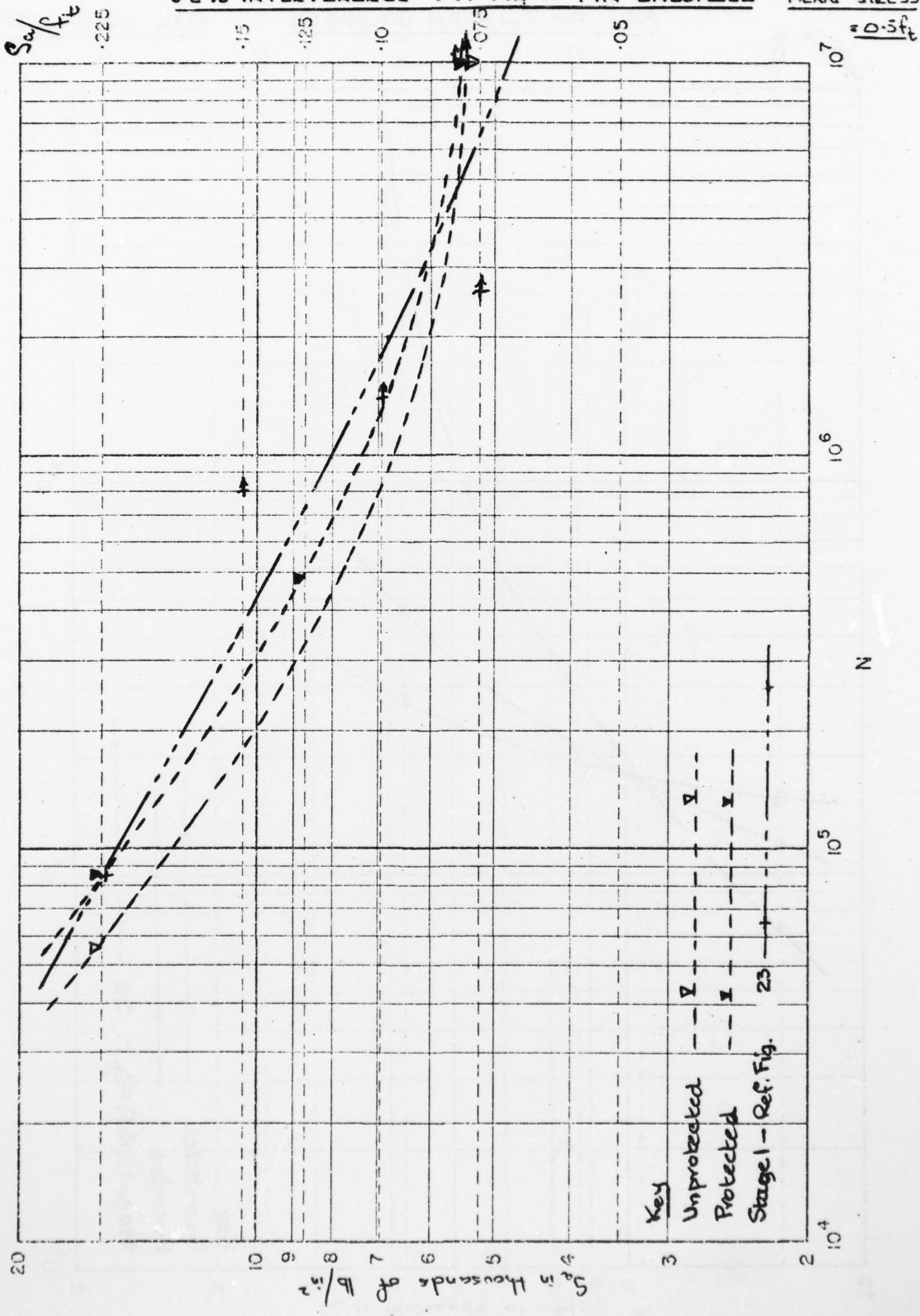
FIGURE 9

MEDIUM SIZE, TYPE 2A 5/16 – d/D = 1/4

Ref: TABLE 9B

0.8% INTERFERENCE FIT PIN – PIN UNLOADED

MEAN STRESS = $0.5f_t$

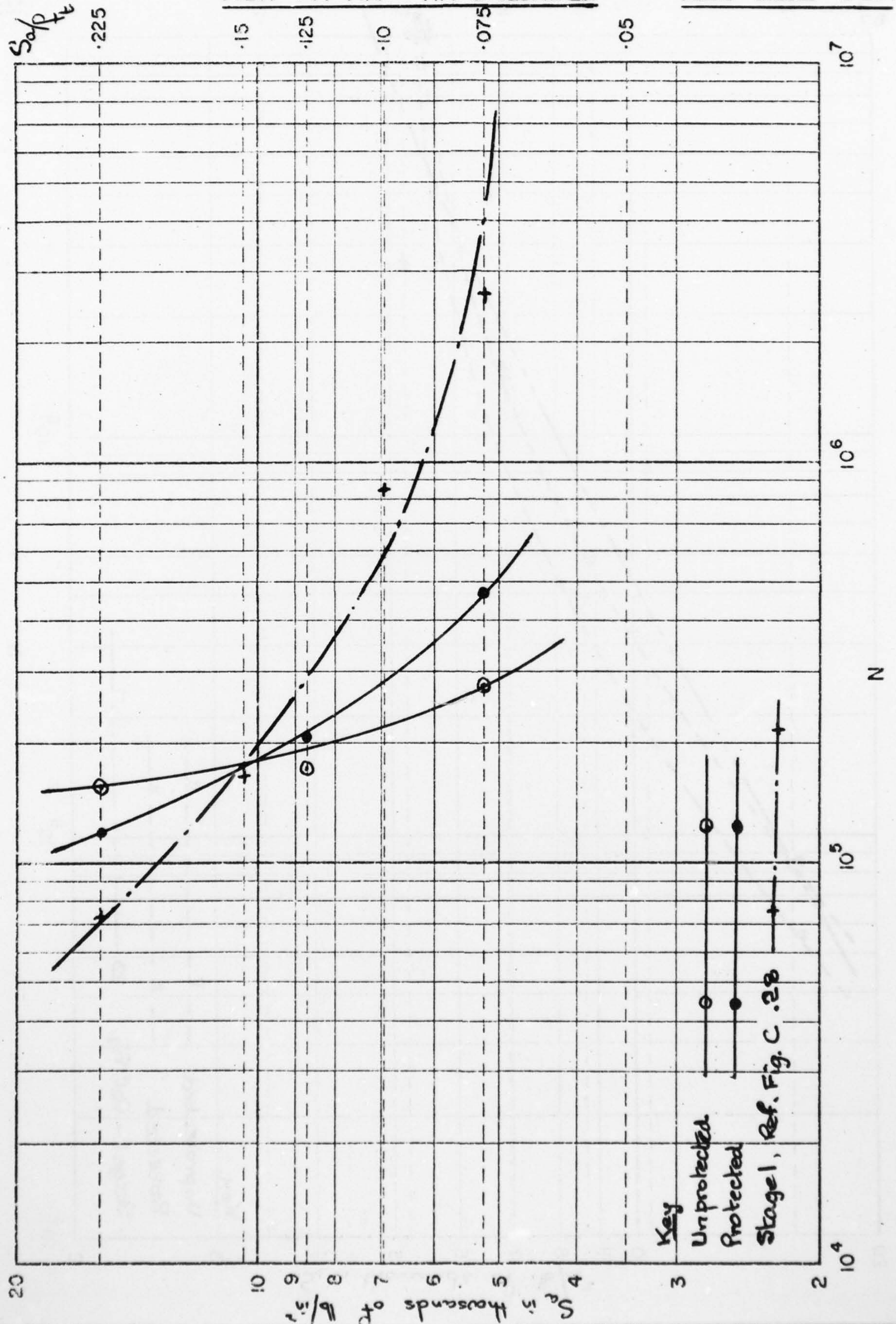


S.1. Nº 8 - EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 10 MEDIUM SIZE, TYPE 2C $^{15}/_{32}$ - $d/_D = 3/_8$ Ref: TABLE 9C

PUSH FIT PIN - PIN UNLOADED MEAN STRESS = $0.25 f_t$



S.I. N° 8 – EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

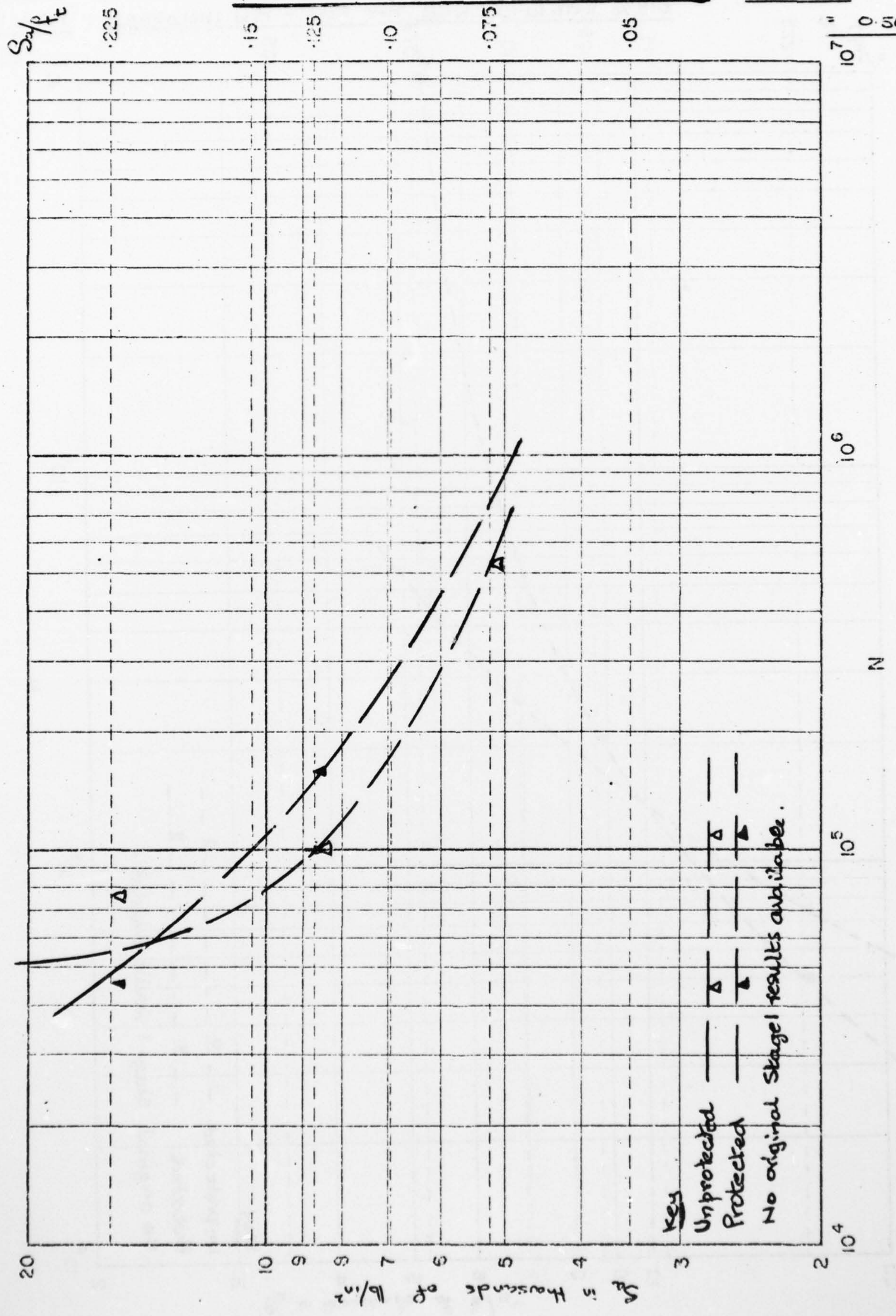
FIGURE 11

MEDIUM SIZE, TYPE 2C 15/32, – $d/D = 3/8$

Ref: TABLE 9C

0.4% INTERFERENCE FIT PIN – PIN UNLOADED

MEAN STRESS $= 0.50 f_t$

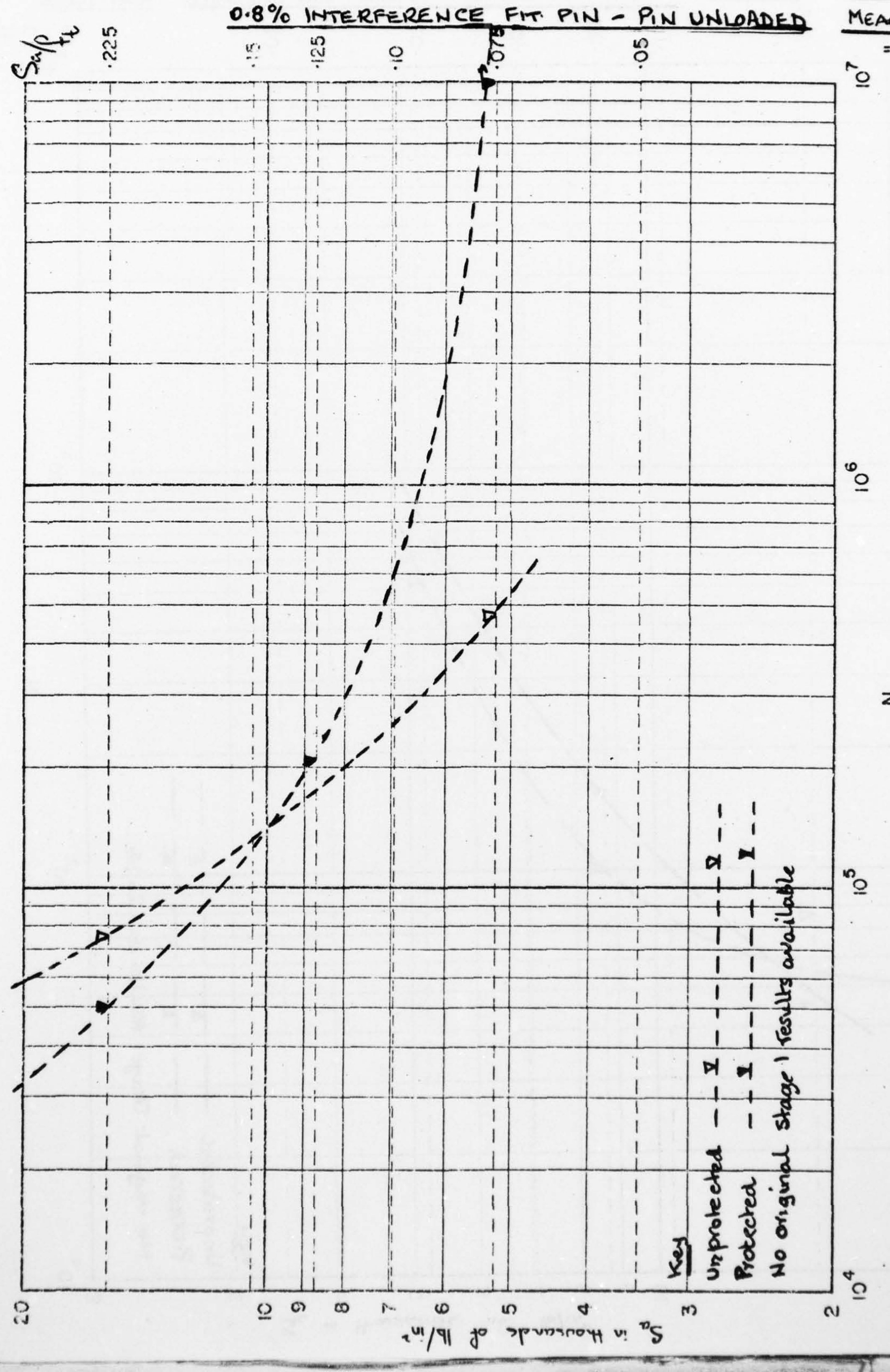


SJ. Nº 8 - EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 12 MEDIUM SIZE, TYPE 2C 15/32 - $d/D = 3/8$ Ref: TABLE 9C

0.8% INTERFERENCE FIT PIN - PIN UNLOADED MEAN STRESS $= 0.50 f_t$

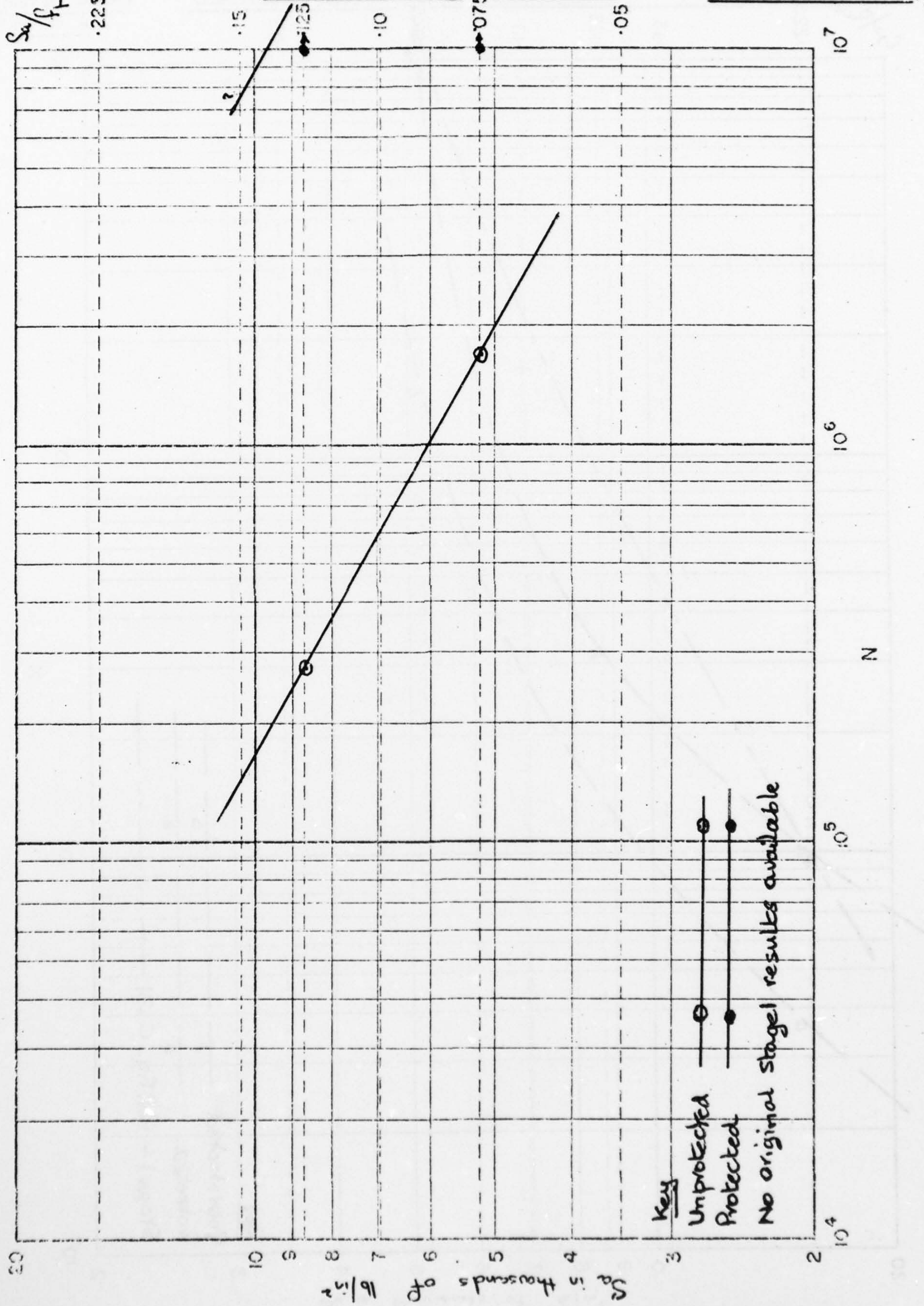


S.I. No 8 – EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 13 MEDIUM SIZE, TYPE 2 C 5/8 – d/D = 1/2 Ref: TABLE 9 D

PUSH FIT PIN – PIN UNLOADED MEAN STRESS = 0.25 f_t

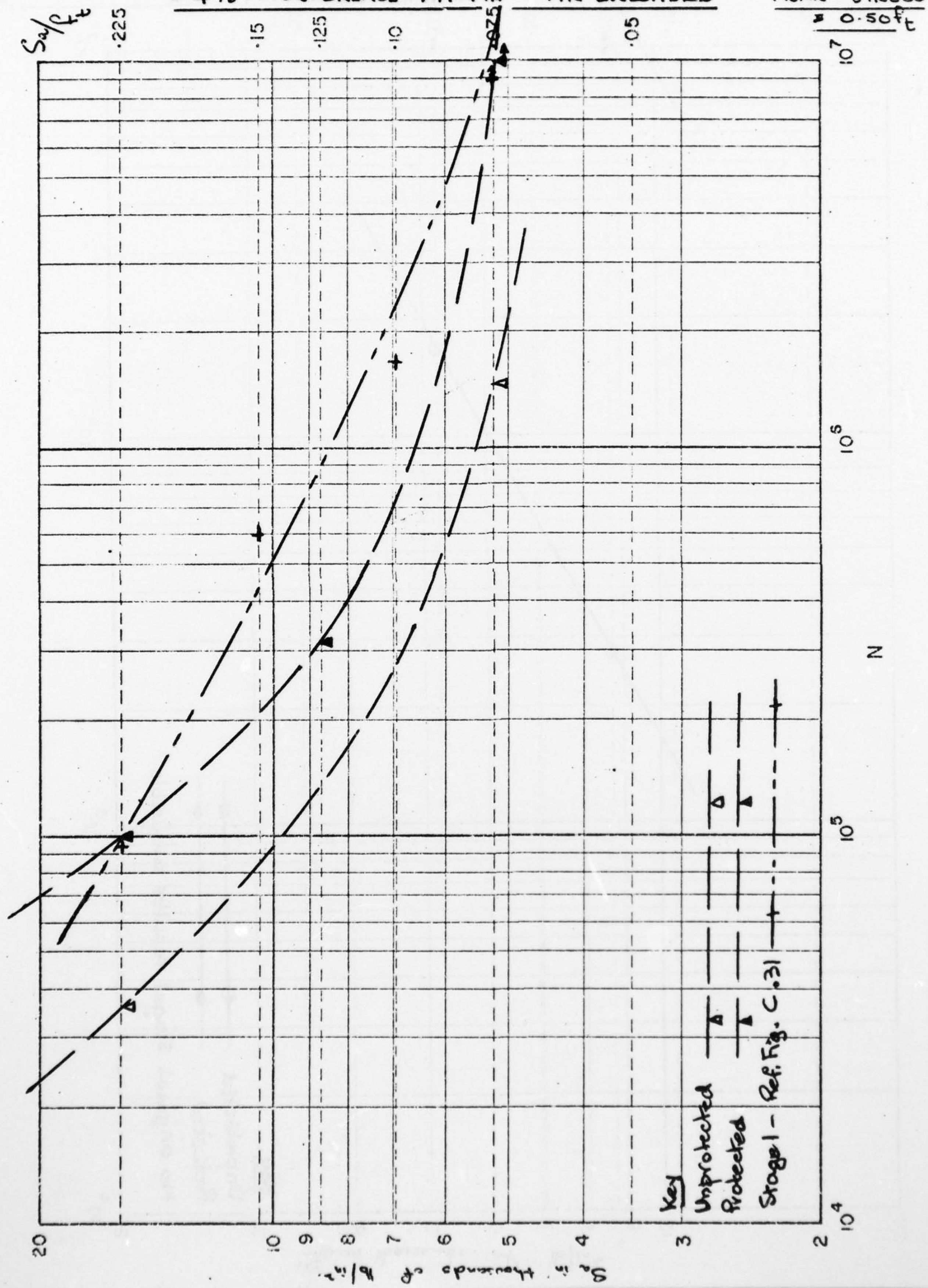


S.I. No 8 – EXPOSURE TESTS

ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 14 MEDIUM SIZE, TYPE 2 C 5/8 – d/D = 1/2 Ref. TABLE 9 D

0·4% INTERFERENCE FIT PIN – PIN UNLOADED MEAN STRESS = 0·50 f_t

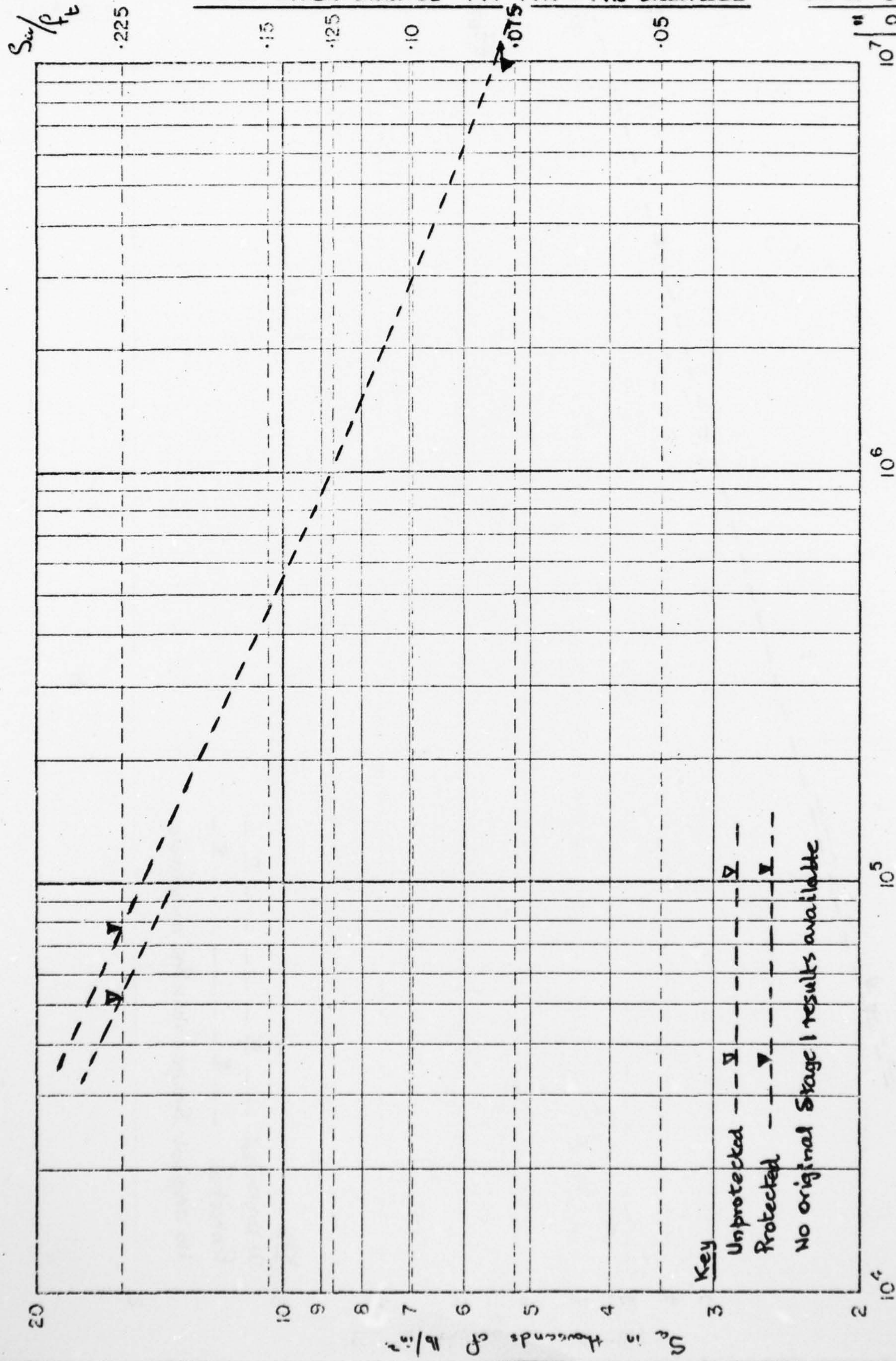


S.I. Nº 8 – EXPOSURE TESTS

ENDURANCES OF STAGE 1 TYPE SPECIMENS

FIGURE 15 — MEDIUM SIZE, TYPE 2C 5/8 – d/D = 1/2 — Ref. TABLE 9 D

0.8 % INTERFERENCE FIT PIN – PIN UNLOADED — MEAN STRESS = 0.50 f_t

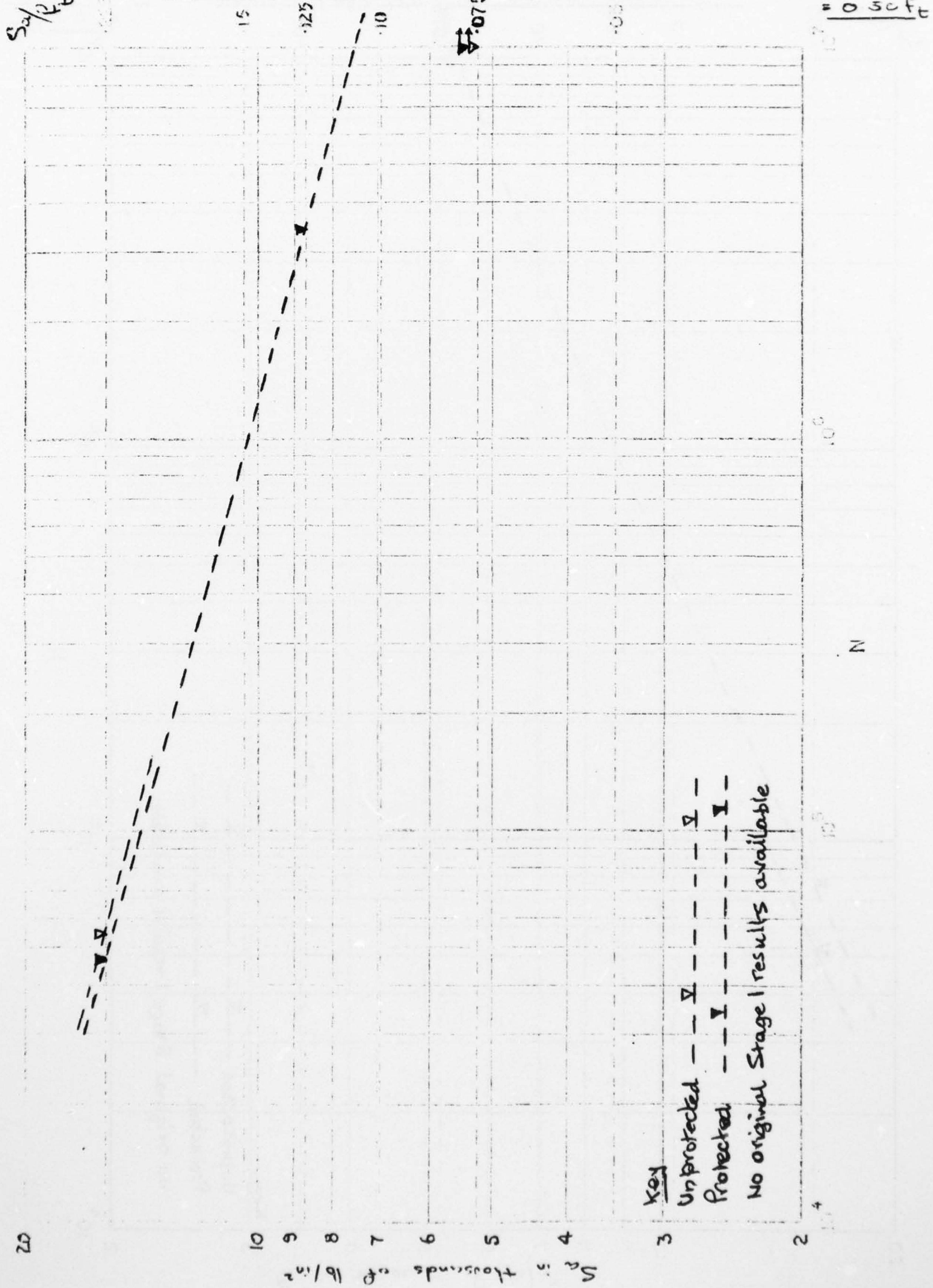


S.I. Nº 8 - EXPOSURE TESTS

82 ENDURANCES OF STAGE I TYPE SPECIMENS

FIGURE 16 SMALL SIZE, TYPE 4C 9/32 - d/D = 3/8 Ref: TABLE 9 E

0.8% INTERFERENCE FIT PIN — PIN UNLOADED MEAN STRESS = 0 scf$_t$



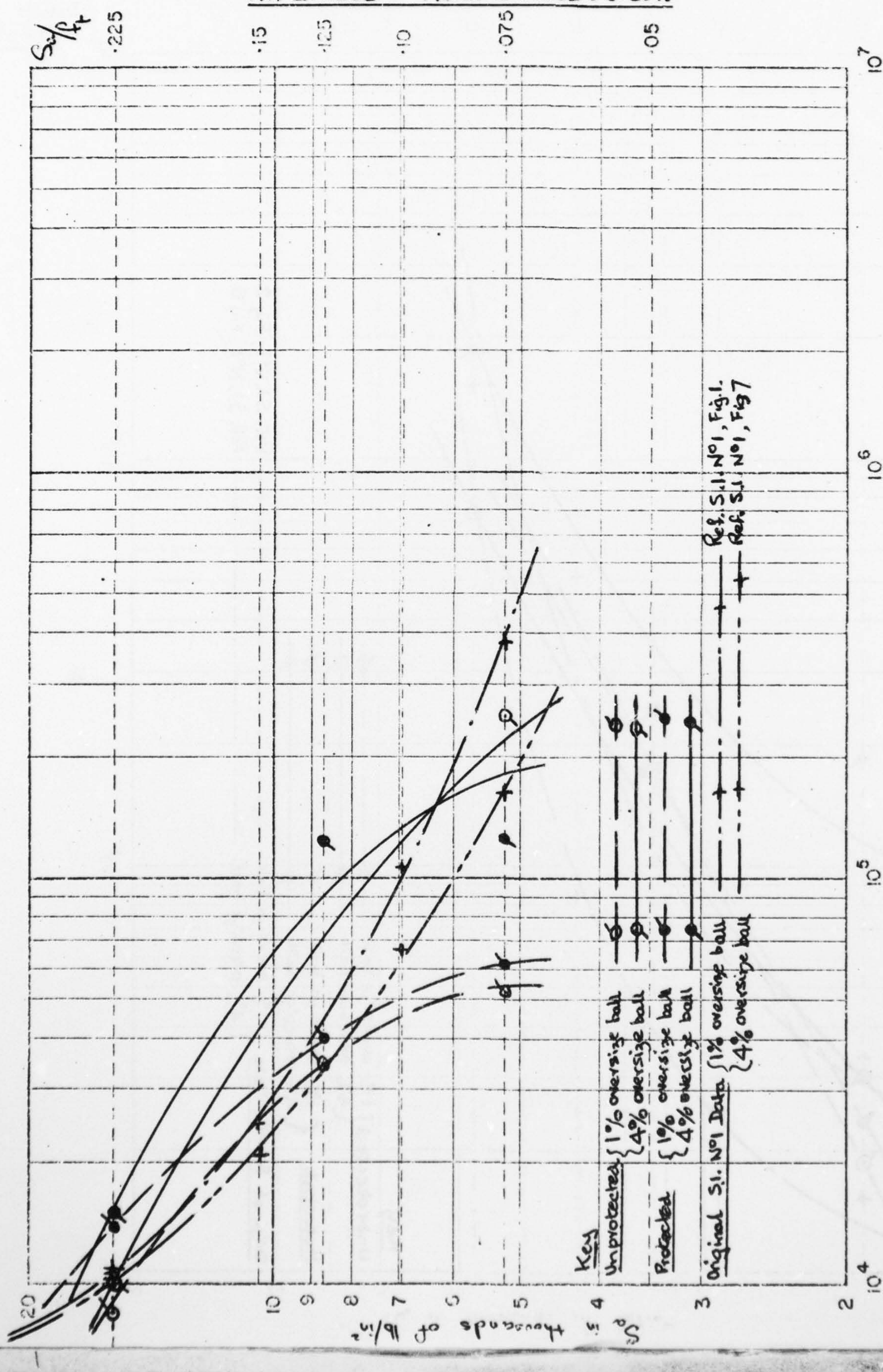
S.I. N°8 - EXPOSURE TESTS

ENDURANCES OF S.I. N°1 TYPE SPECIMENS

FIGURE 17 MEDIUM SIZE, TYPE 2B 5/16 - d/D = 1/4 Ref. - TABLE 10 A

INTERFERENCE PRE-STRESSED HOLES

PIN LOADED - MEAN STRESS = 0.25 f_t

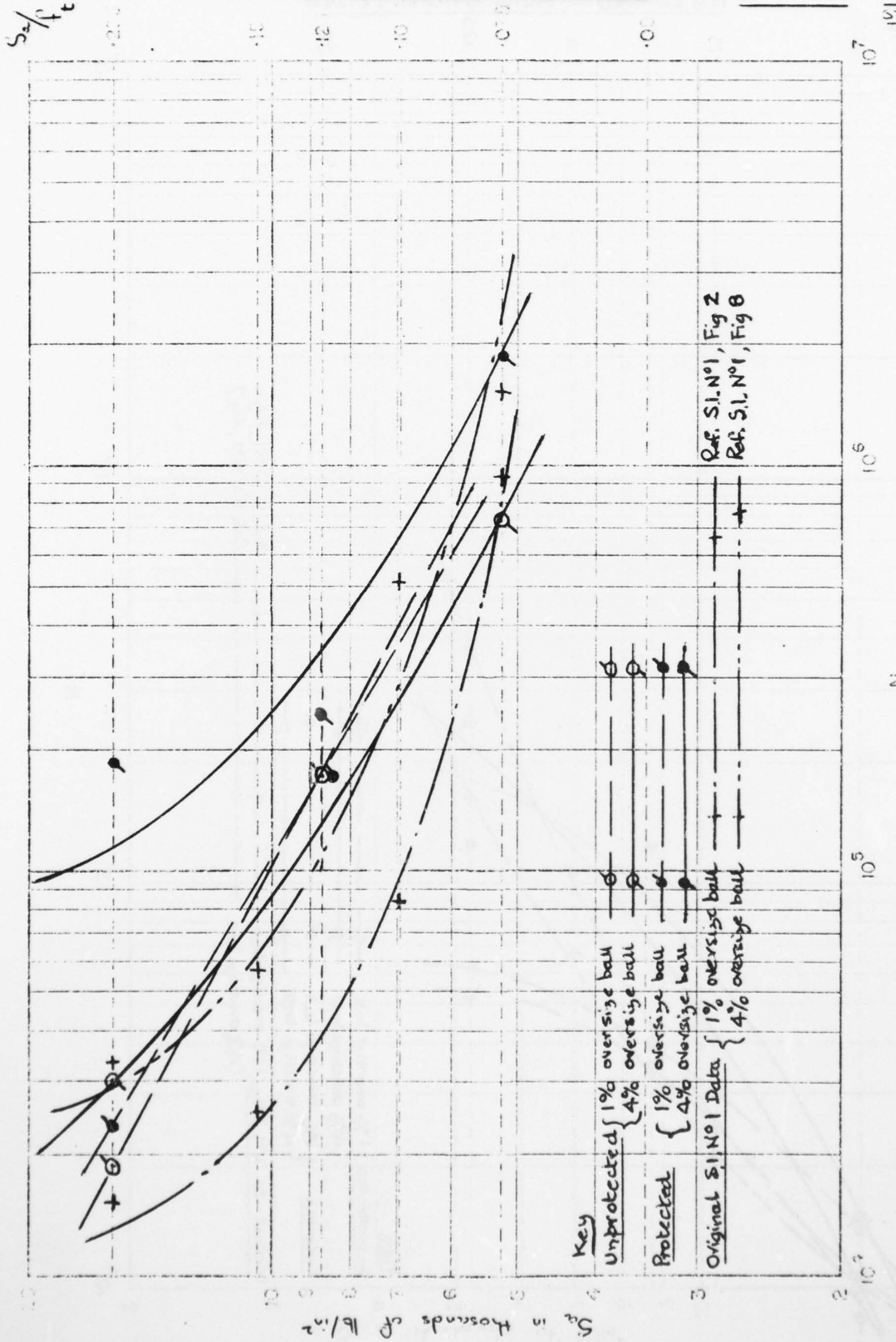


S.I. N°8 EXPOSURE TESTS

ENDURANCES OF S.I. N°1 TYPE SPECIMENS

FIGURE 18 MEDIUM SIZE, TYPE $2D\frac{15}{32} - d/D = 3/8$ Ref. - TABLE 10 B

INTERFERENCE PRE-STRESSED HOLES PIN LOADED - MEAN STRESS $= 0.25 f_t$



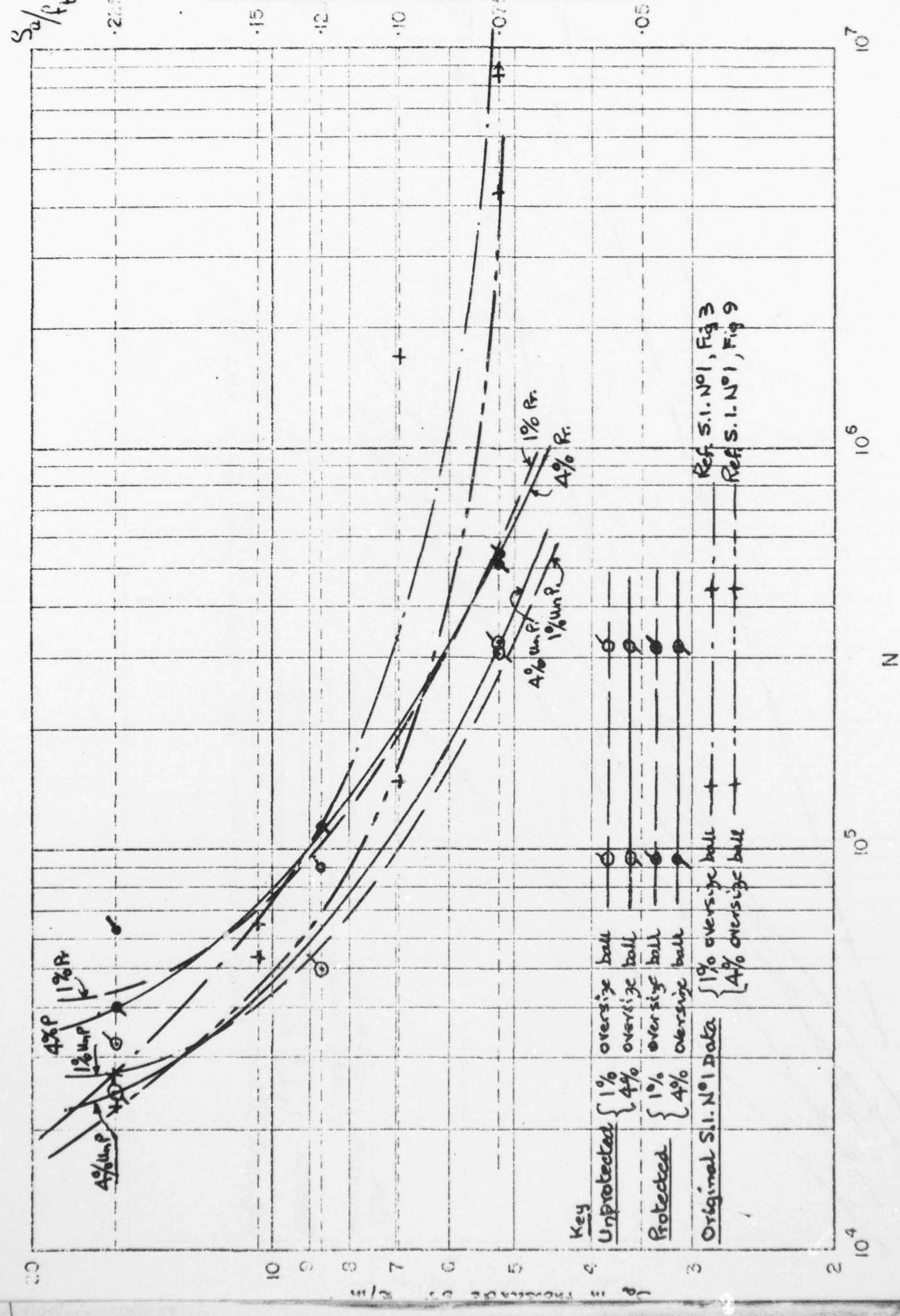
S.I. N° 8 – EXPOSURE TESTS

ENDURANCES OF S.I. N°1 TYPE SPECIMENS

FIGURE 19 MEDIUM SIZE, TYPE 2D 5/8 – d/D = 1/2 Ref. TABLE 10 C

INTERFERENCE PRE-STRESSED HOLES

PIN LOADED – MEAN STRESS = 0.25 f_t



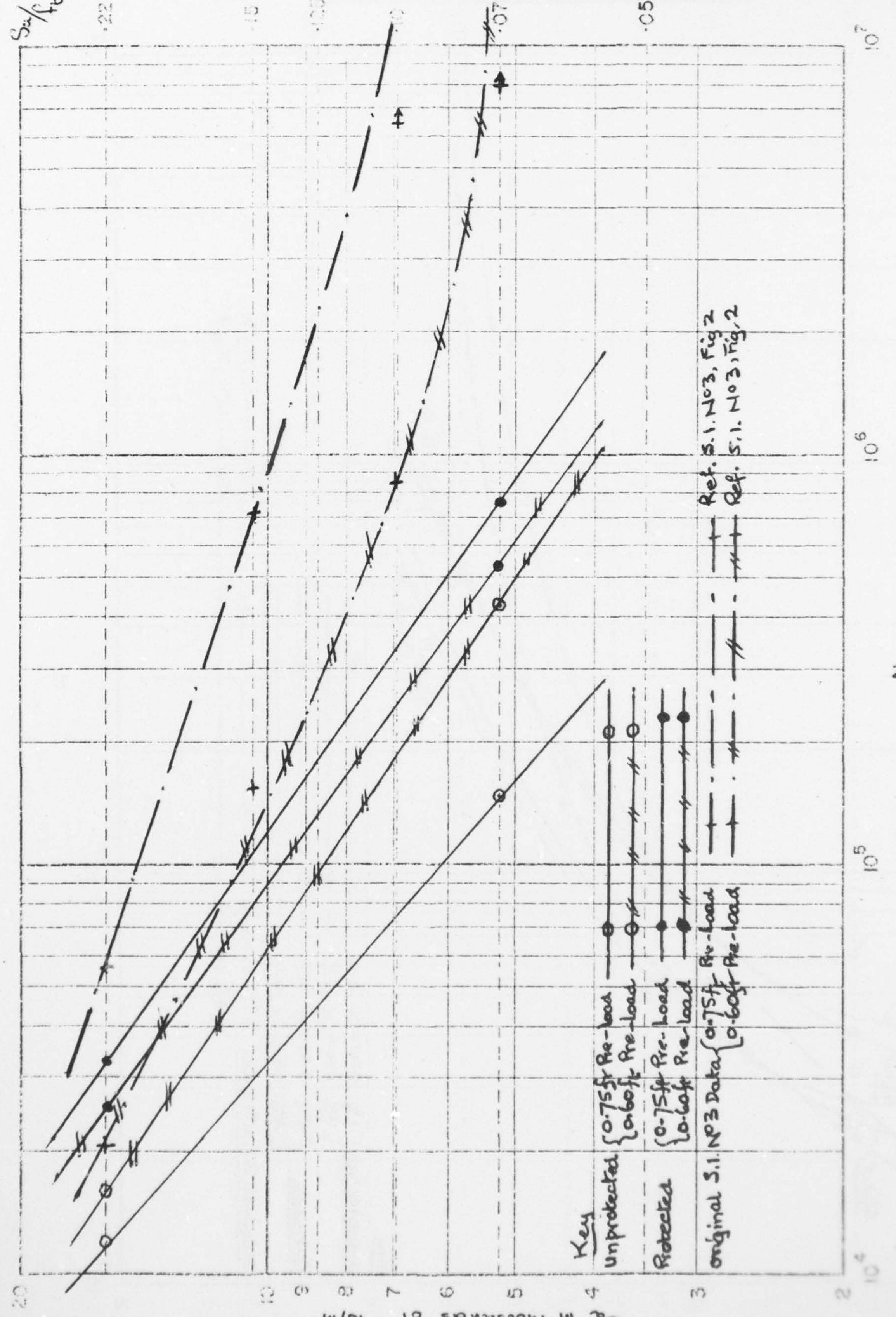
S.I. Nº 8 – EXPOSURE TESTS

ENDURANCES OF S.I. Nº3 TYPE SPECIMENS.

FIGURE 20 — SMALL SIZE, TYPE 4B3/16 – d/D = 1/4 — Ref: TABLES 11A & 11B

PRE-LOADED SPECIMENS – PIN LOADED

PUSH FIT — MEAN STRESS = 0·25f_t



AD-A064 083 DEFENCE RESEARCH INFORMATION CENTRE ORPINGTON (ENGLAND) F/G 13/5
BOLTED JOINT FATIGUE PROGRAMME. VOLUME 4. STAGE 2. SUPPLEMENTAR--ETC(U)
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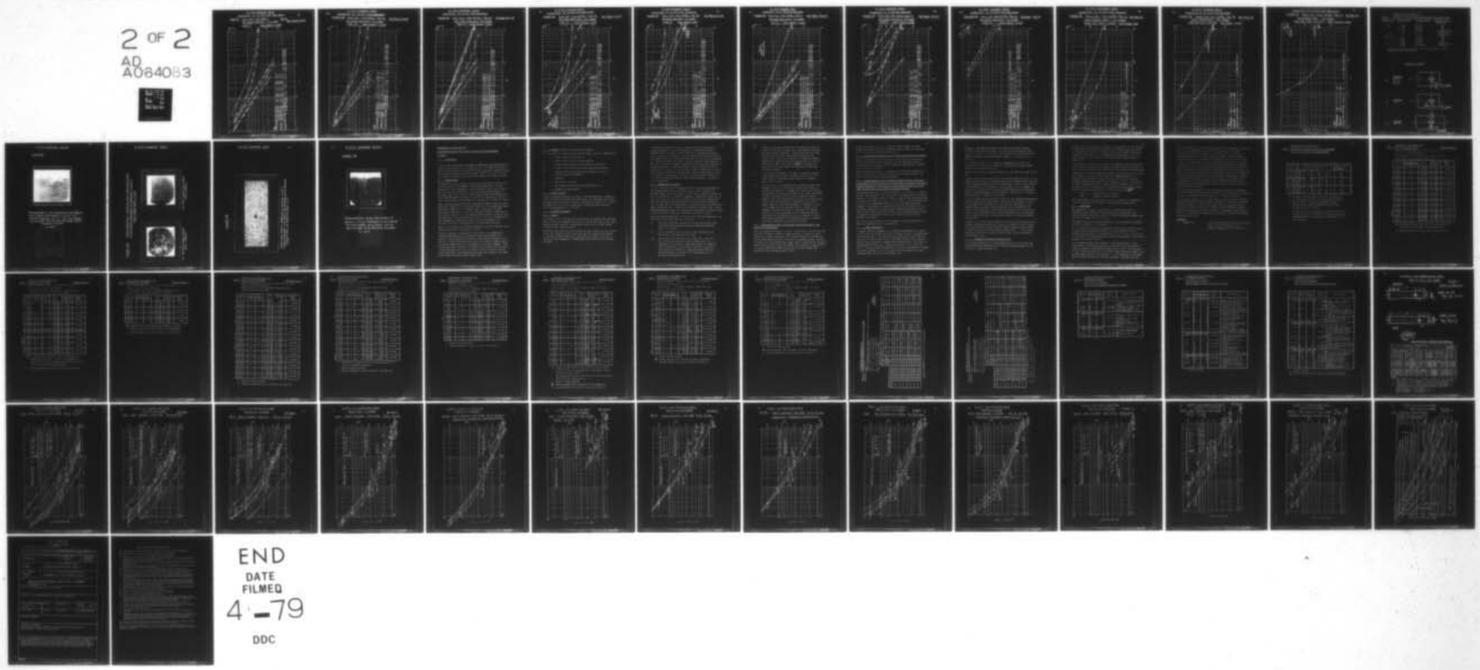

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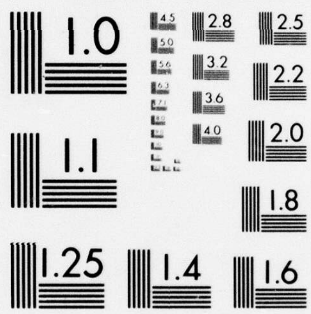

MICROCOPY RESOLUTION TEST CHART
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S.I. Nº B - EXPOSURE TESTS

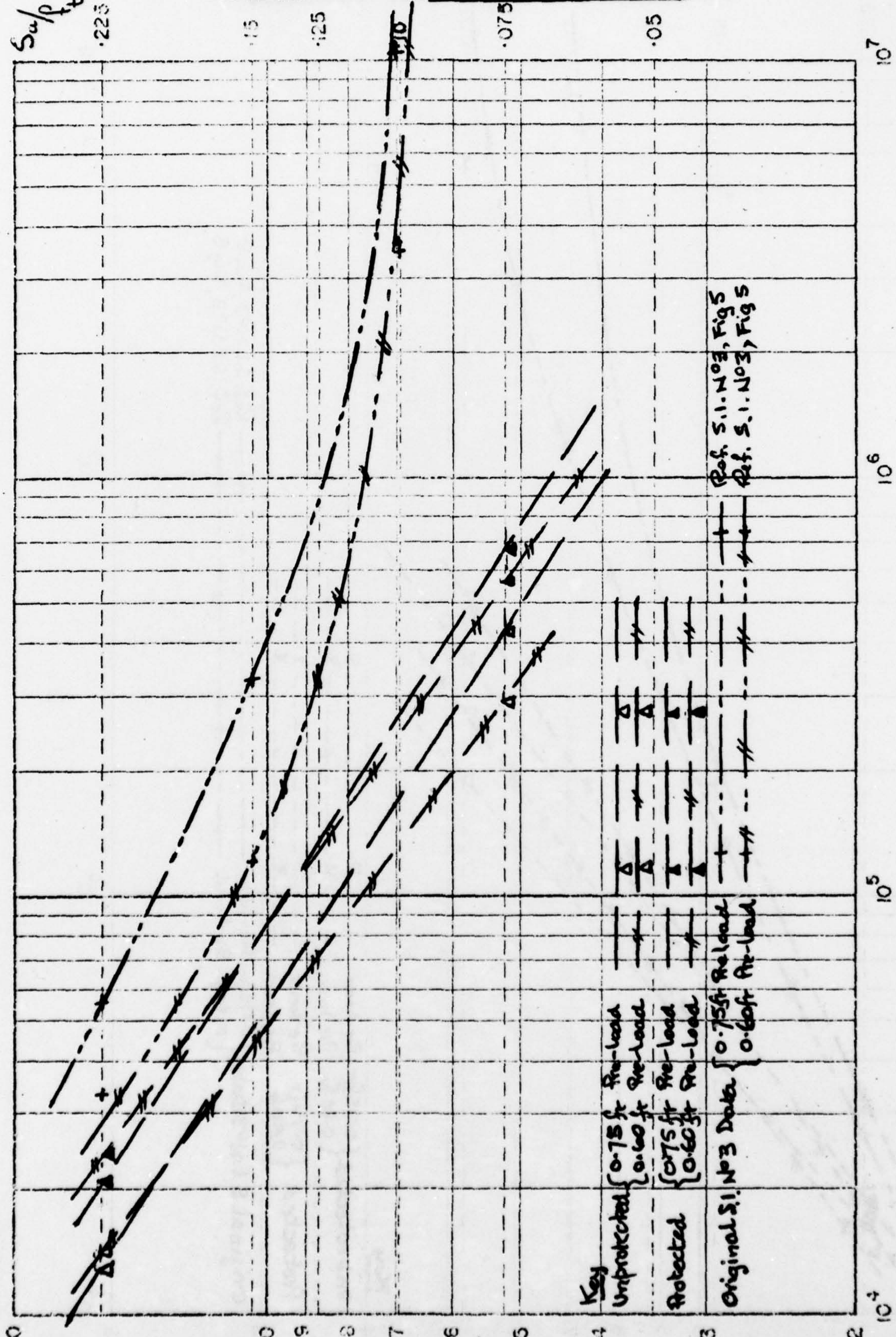
ENDURANCES OF S.I. Nº 3 TYPE SPECIMENS

FIGURE 21 SMALL SIZE, TYPE 4B3/16 d/D = 1/4

PRE-LOADED SPECIMENS - PIN LOADED

Ref. TABLES 11A & 11B

0·4% I.F MEAN STRESS = 0·25ft

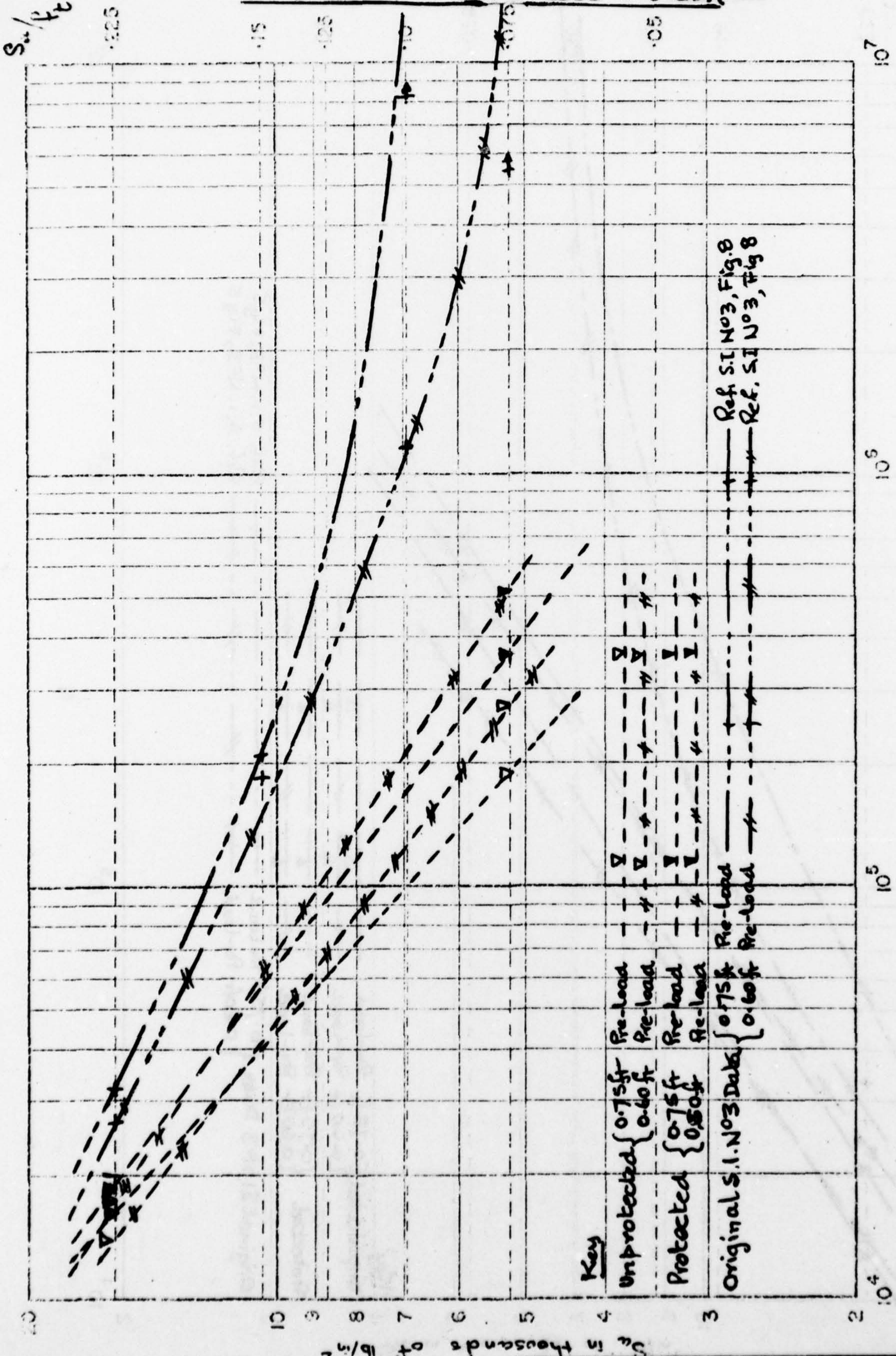


ENDURANCES OF S.I. No3 TYPE SPECIMENS

FIGURE 22 SMALL SIZE, TYPE 4B 3/16 - d/D = 1/4 Ref: TABLES 11A & 11B

PRE-LOADED SPECIMENS - PIN LOADED

0.8% I.F. MEAN STRESS = 0.25ft



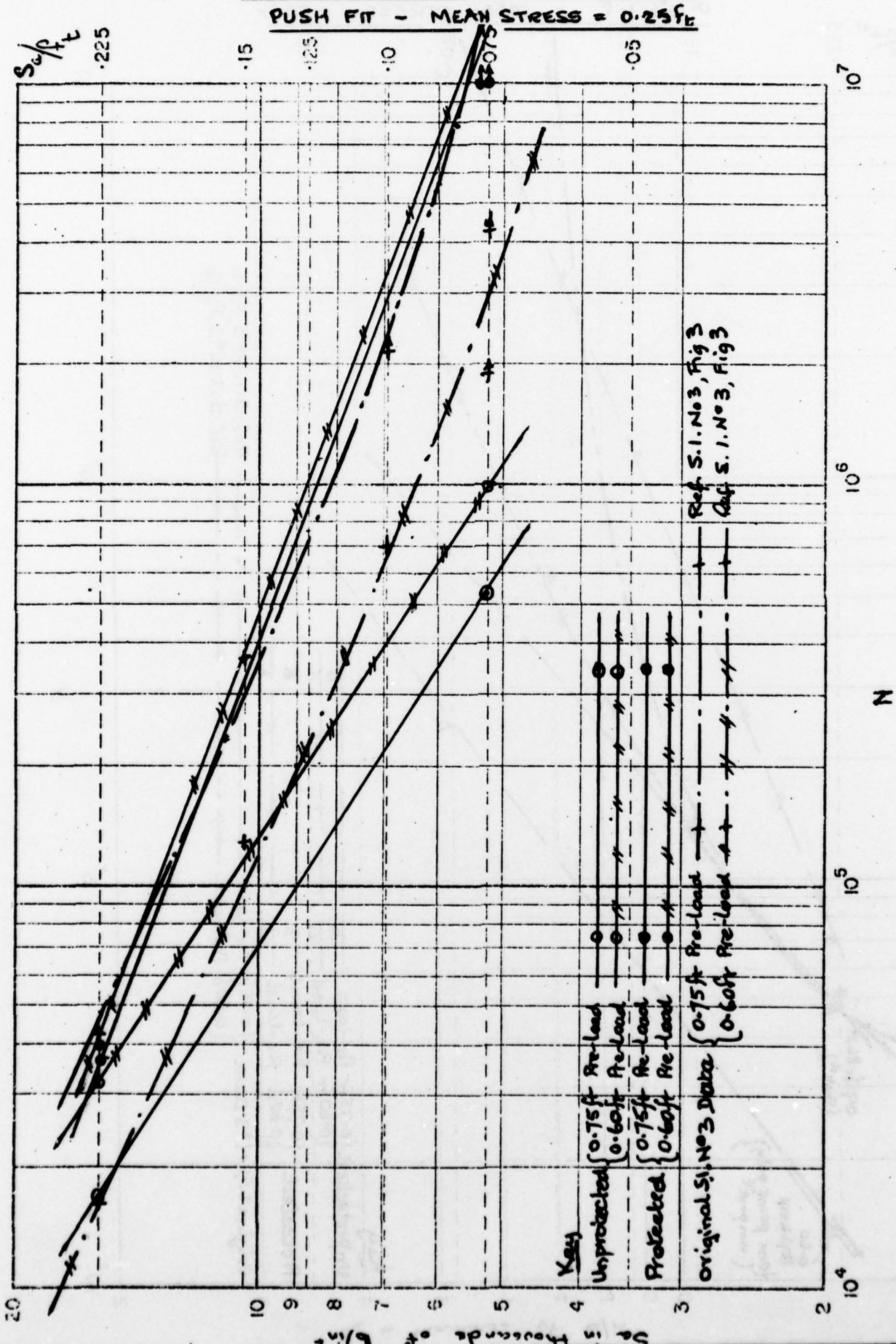
S.I. No 8 - EXPOSURE TESTS

ENDURANCES OF S.I. No 3 TYPE SPECIMENS

FIGURE 23 SMALL SIZE, TYPE 4D 9/32 - d/D - 3/8 Ref: TABLES 11C & 11D

PRE-LOADED SPECIMENS - PIN LOADED

PUSH FIT - MEAN STRESS = 0.25 f_t



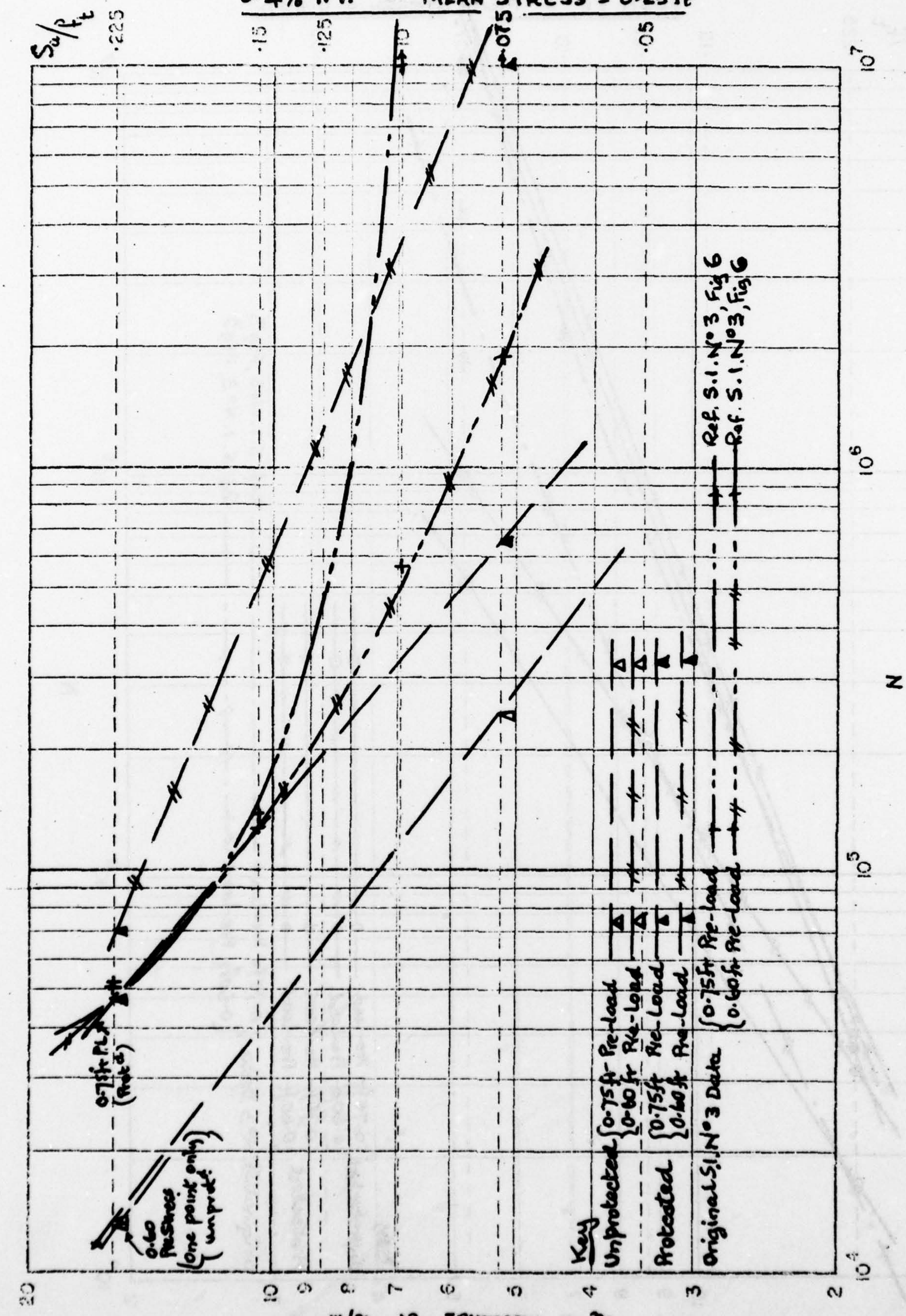
S.I. No 8 - EXPOSURE TESTS

ENDURANCES OF S.I. No 3 TYPE SPECIMENS

FIGURE 24 — SMALL SIZE. TYPE 4D 9/32 - d/D = 3/8 — Ref: TABLES 11C & 11D

PRE-LOADED SPECIMENS - PIN LOADED

0.4% I.F. - MEAN STRESS = 0.25 ft



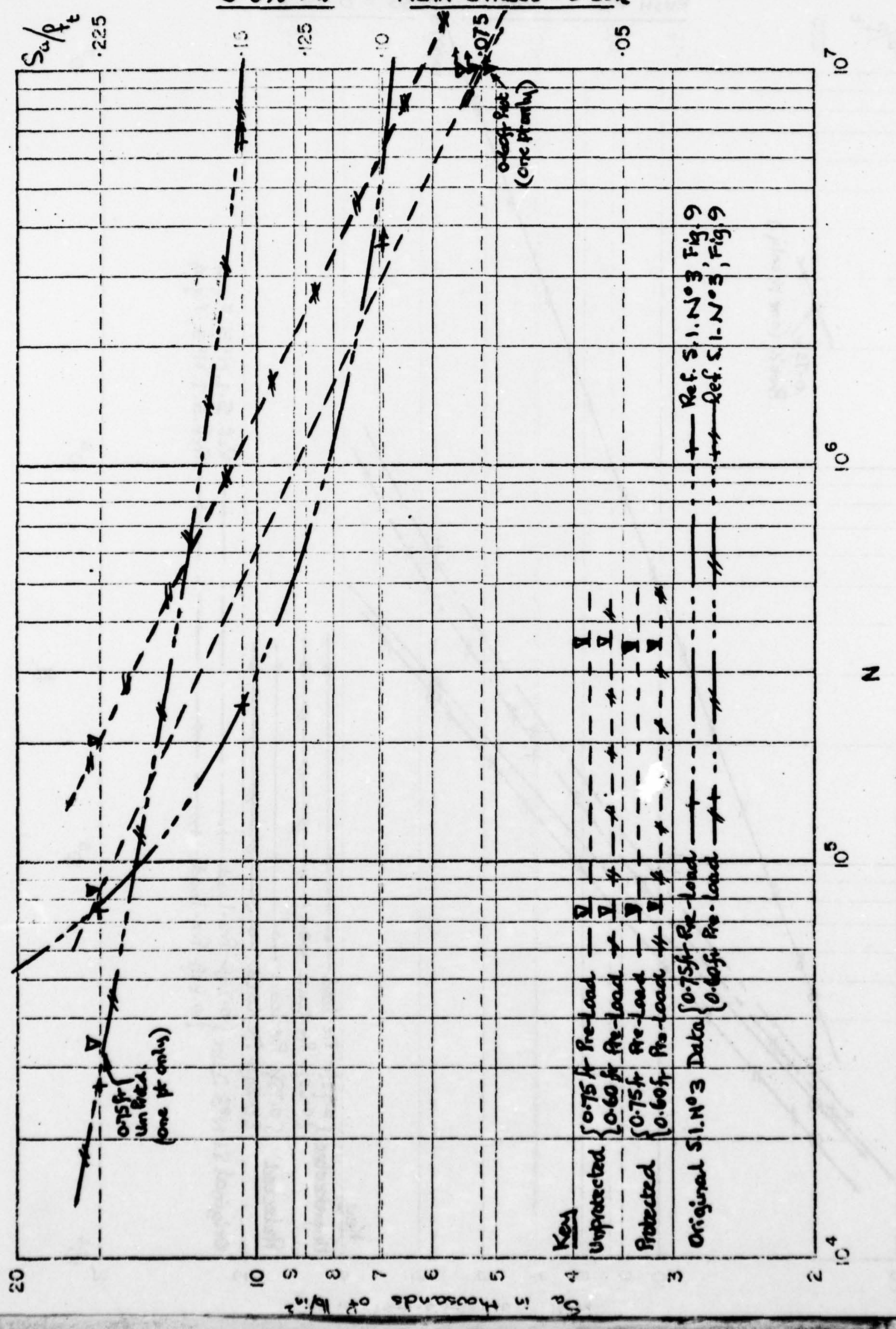
S.I. N°8 - EXPOSURE TESTS

ENDURANCES OF S.I. N°3 TYPE SPECIMENS

FIGURE 25 — SMALL SIZE, TYPE 4 D 9/32 - d/D = 3/8 — Ref: TABLES 11C & 11D

PRE-LOADED SPECIMENS - PIN LOADED

0.8% I.F. — MEAN STRESS = 0.25 f_t



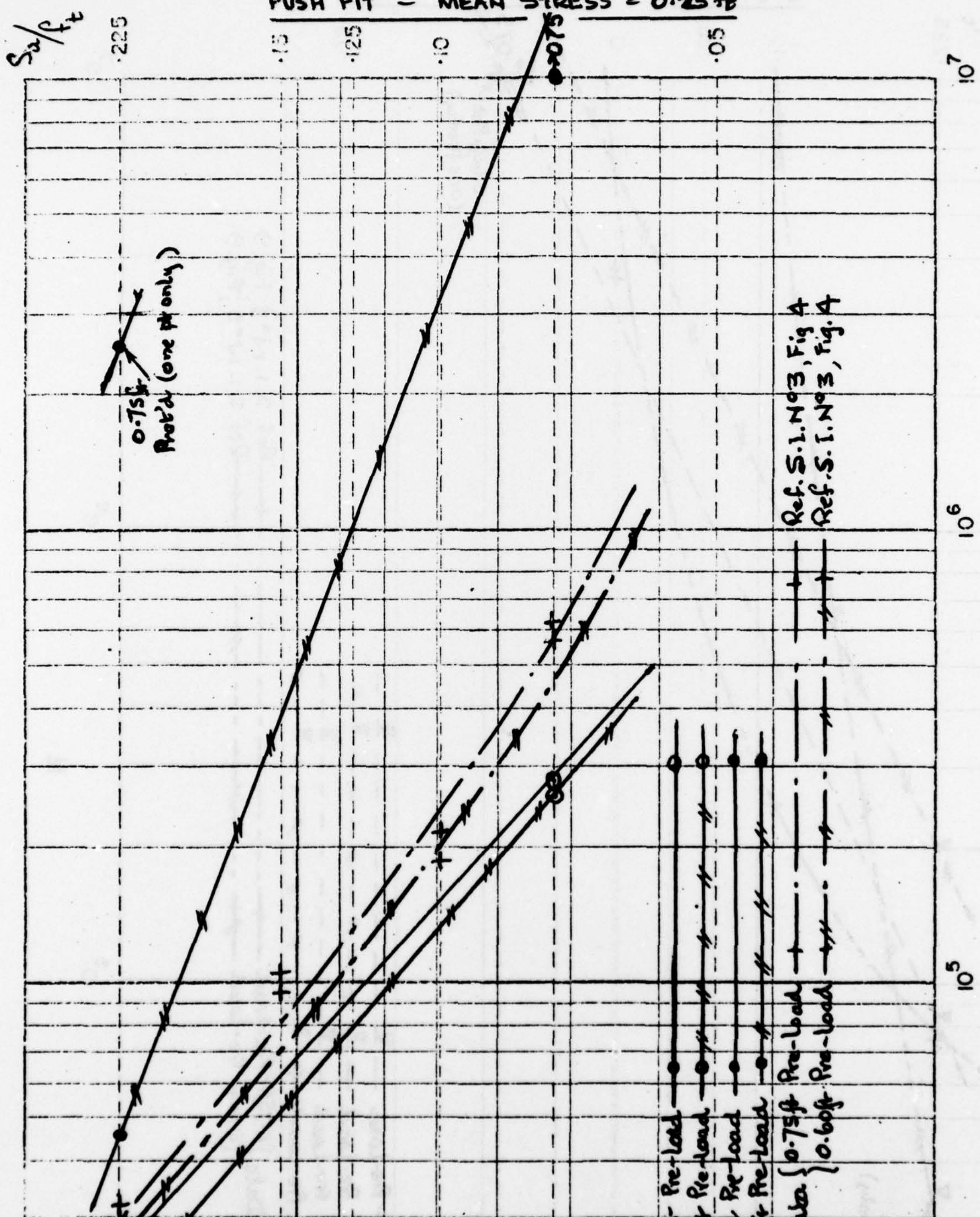
S.I. Nº 8 - EXPOSURE TESTS

ENDURANCES OF S.I. Nº3 TYPE SPECIMENS

FIGURE 26 SMALL SIZE, TYPE 4D3/8 — d/D = 1/2 Ref: TABLES 11E & 11F

PRE-LOADED SPECIMENS - PIN LOADED

PUSH FIT - MEAN STRESS = 0.25 ft



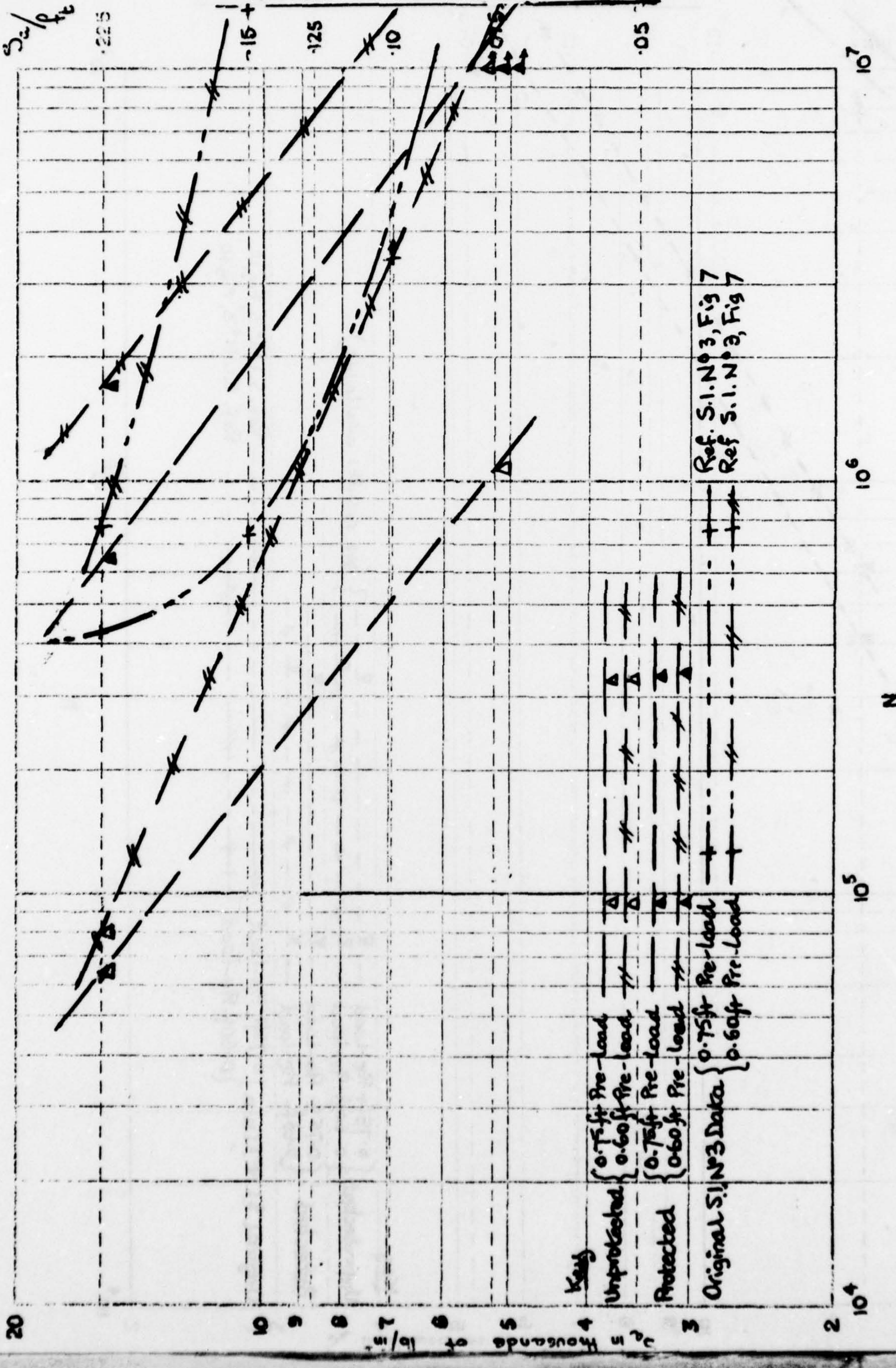
S.I. No 8 - EXPOSURE TESTS

ENDURANCES OF S.I. No 3 TYPE SPECIMENS

FIGURE 27 SMALL SIZE, TYPE 4D 3/8 – d/D = 1/2 Ref: TABLES 11E & 11F

PRE-LOADED SPECIMENS - PIN LOADED

0·4% I.F. MEAN STRESS = 0·25 f_t



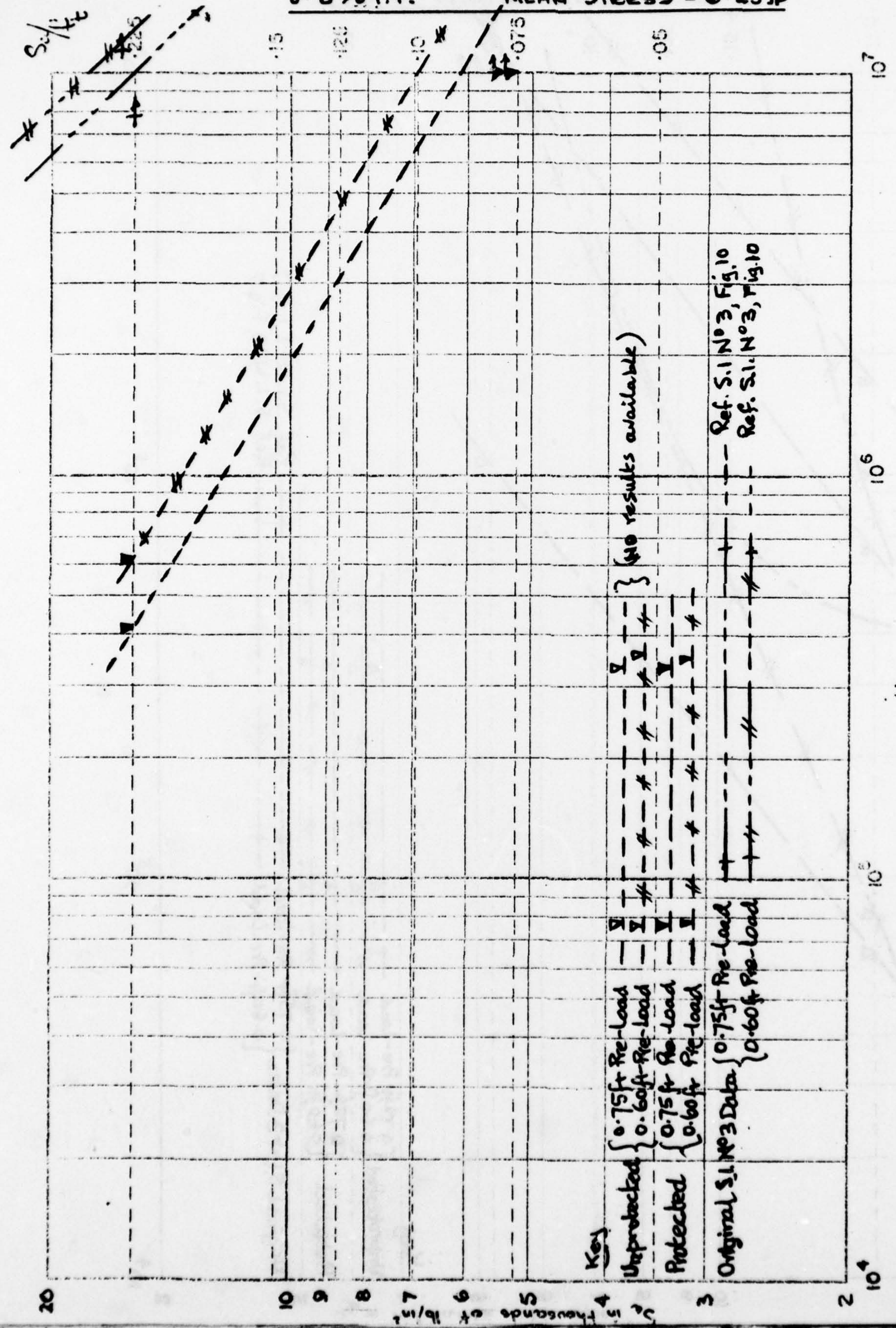
S.I. No 8 - EXPOSURE TESTS.

ENDURANCES OF S.I. No 3 TYPE SPECIMENS

FIGURE 28 SMALL SIZE, TYPE $4D^{3}/_{8}$ - $d/D = 1/2$ Ref: TABLES 11E & 11F

PRE-LOADED SPECIMENS - PIN LOADED

0·8% I.F. MEAN STRESS = 0·25 f_t



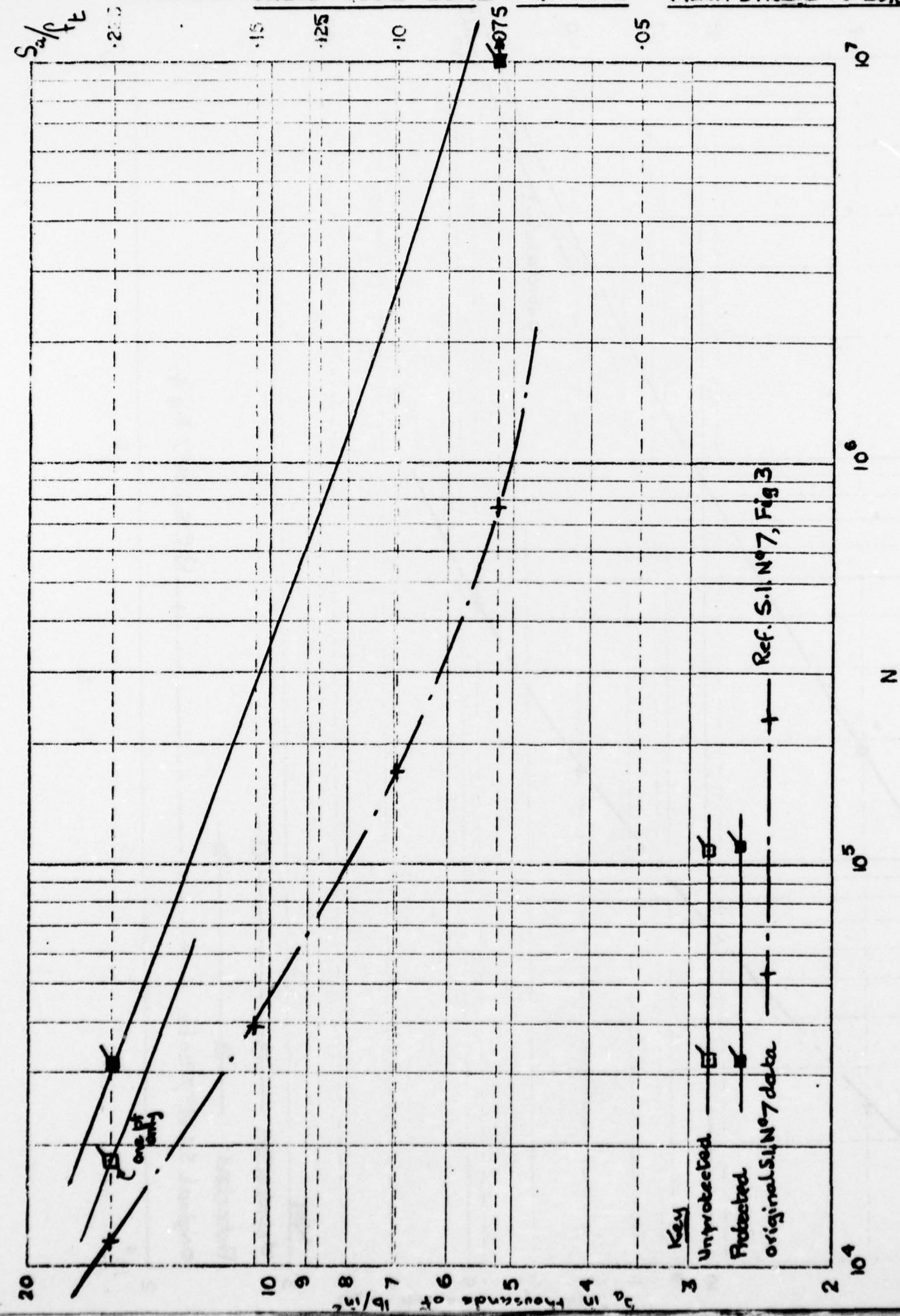
S.I. N° 8 – EXPOSURE TESTS

ENDURANCES OF S.I. N°7 TYPE SPECIMENS

FIGURE 29 MEDIUM SIZE, TYPE 2 B 5/16 – $d/D = 1/4$ Ref: TABLE 12A

PRESS-FORMED RADII – PIN LOADED

PRESS TOOL LOAD = 4.0 TONS MEAN STRESS = $0.25 f_t$



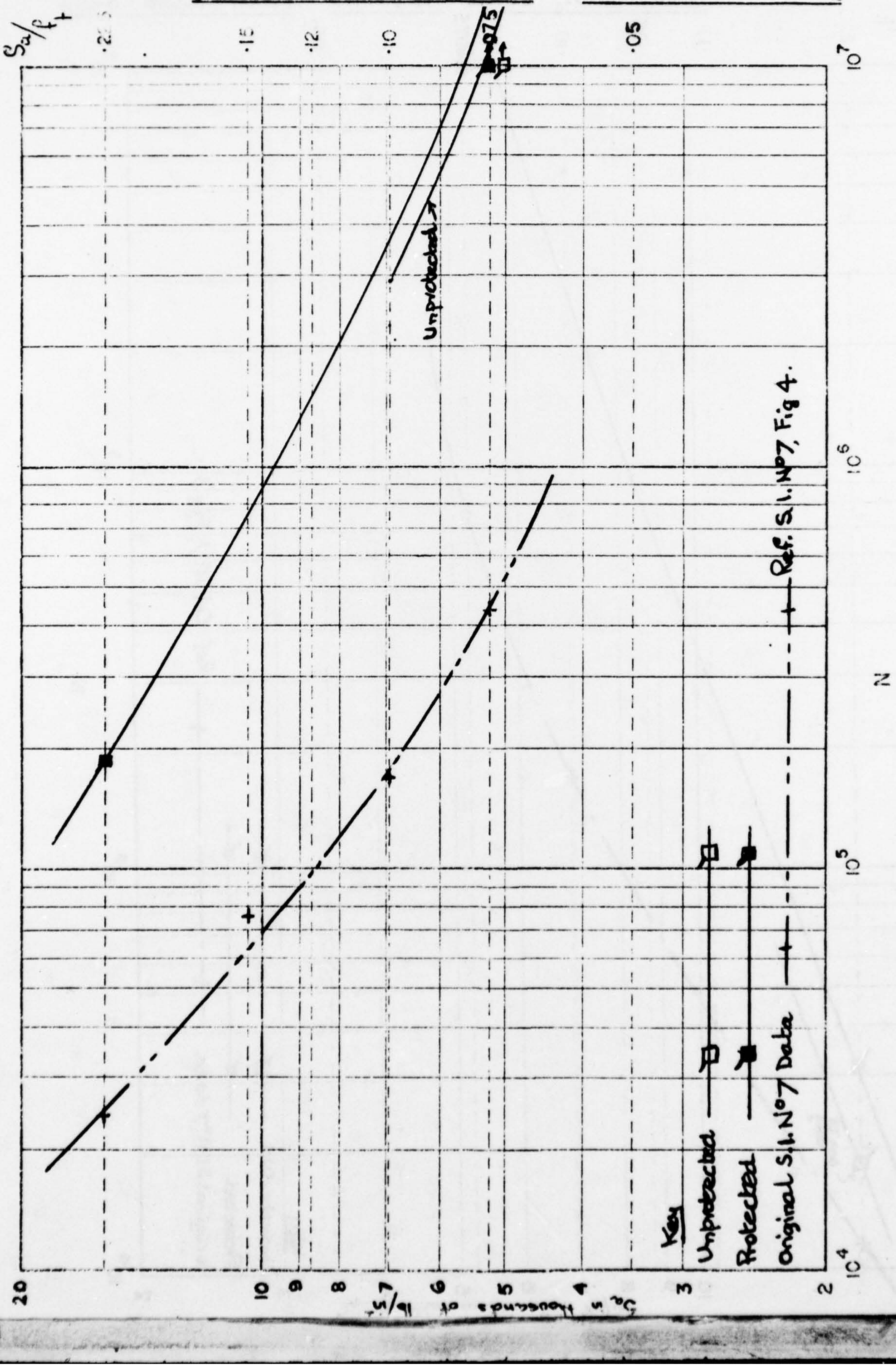
S.I. N° 8 - EXPOSURE TESTS

ENDURANCES OF S.I. N°7 TYPE SPECIMENS

FIGURE 30 MEDIUM SIZE, TYPE $2D^{15}/_{32}$ - $d/_D = 3/_8$ Ref: TABLE 12B

PRESS-FORMED RADII - PIN LOADED

PRESS-TOOL LOAD = 4·5 TONS MEAN STRESS = $0{\cdot}25 f_t$



ENDURANCES OF S-1. No 7 TYPE SPECIMENS

FIGURE 31 MEDIUM SIZE, TYPE 2D 5/8 – d/D = 1/2 Ref: TABLE 12C

PRESS-FORMED RADII – PIN LOADED

PRESS TOOL LOAD = 5.0 TONS MEAN STRESS = 0.25 f_{tt}

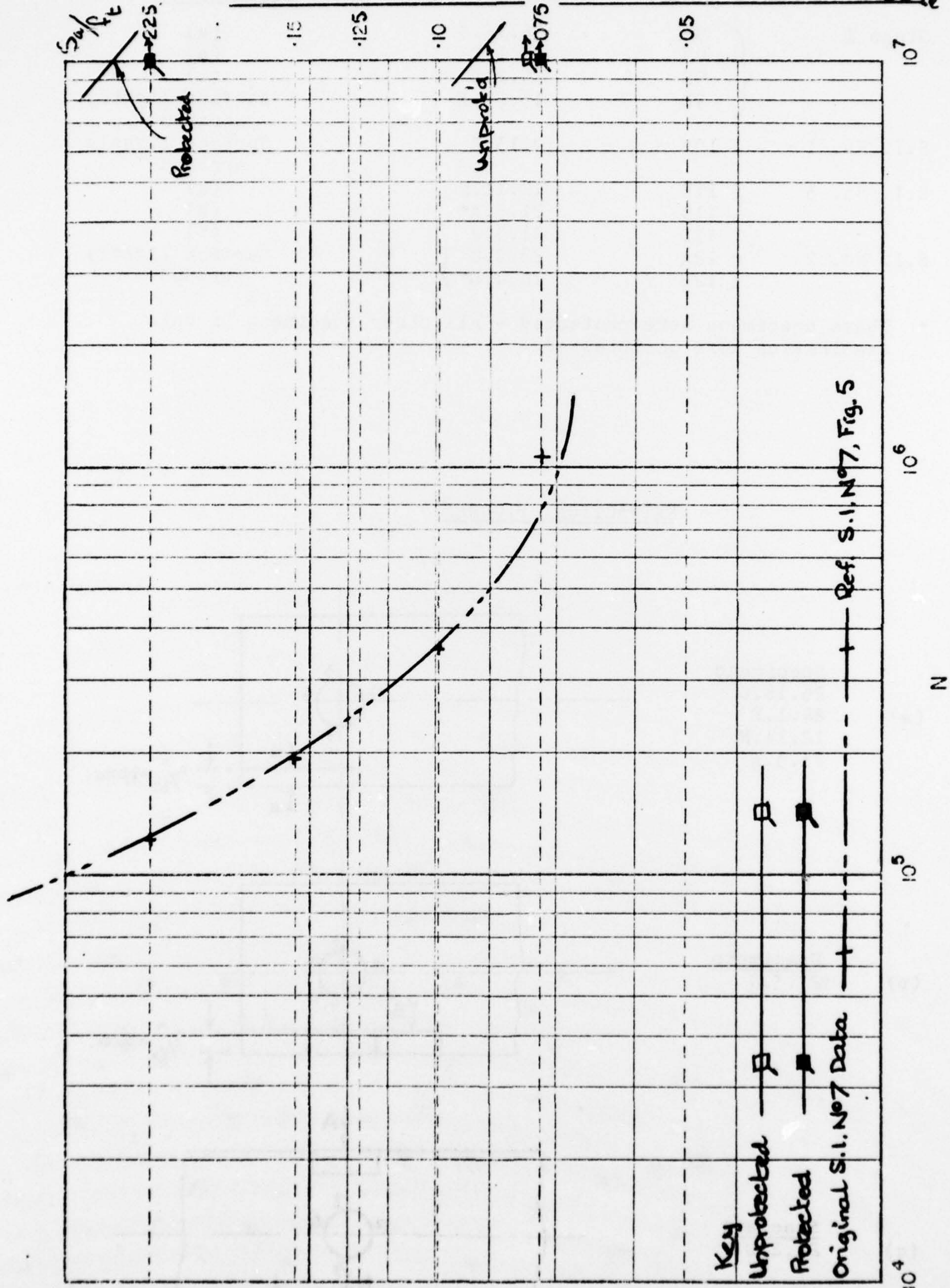


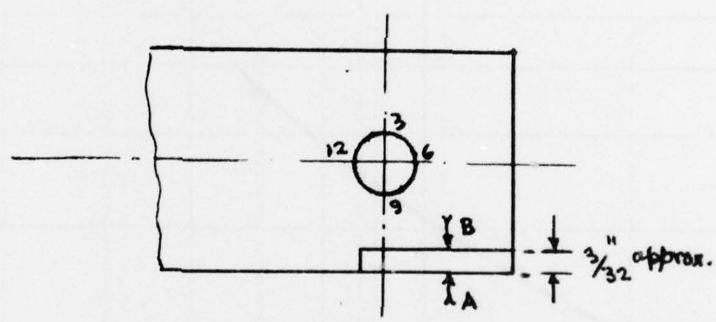
FIGURE 32 EXTRACTION OF MICRO-SPECIMENS FOR EXAMINATION OF FATIGUE FAILURES

SPECIMEN TYPE	REFERENCE TABLE	SPECIMEN IDENTITY	EXTRACTION FIGURE (See below)
Stage 1	9B	26.16.C	(a)
	9B	24.1.E	(a)
	9B	24.2.D	(c)
	9E	13.27.F	Surface lightly abraded
S.I. No. 1	10B	9.13.B	Surface lightly abraded
S.I. No. 3	11B	12.11.N	(a)
	11C	21.3.A*	(a)
	11D	21.3.J	(b)
S.I. No. 7	12A	28.9.C	Surface lightly abraded
	12B	14.4.D*	

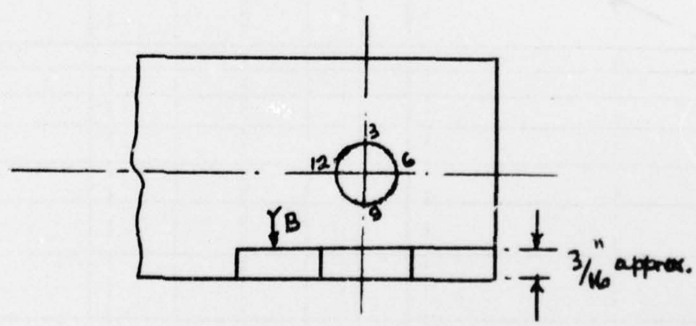
* These specimens were protected - all other specimens in this examination were unprotected.

EXTRACTION FIGURES

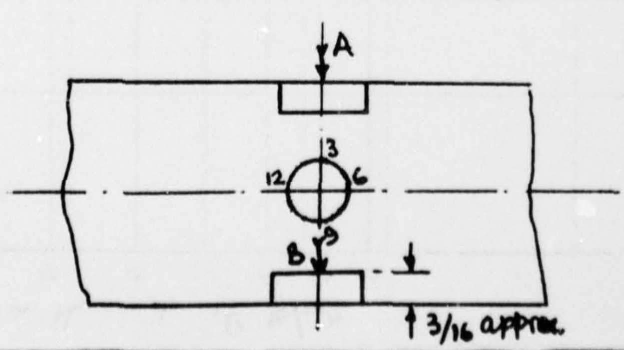
(a) Specimens
26.16.C
24.1.E
12.11.N
21.3.A



(b) Specimens
21.3.J

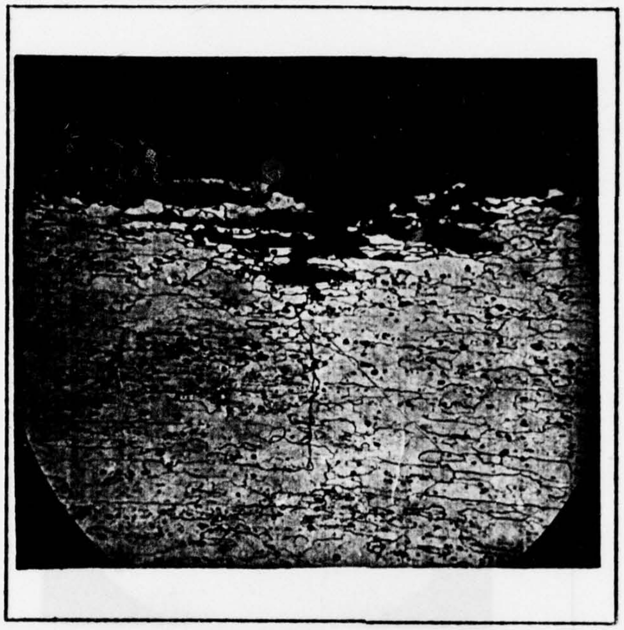


(c) Specimen
24.2.D



S.I. No 8 - EXPOSURE TESTS

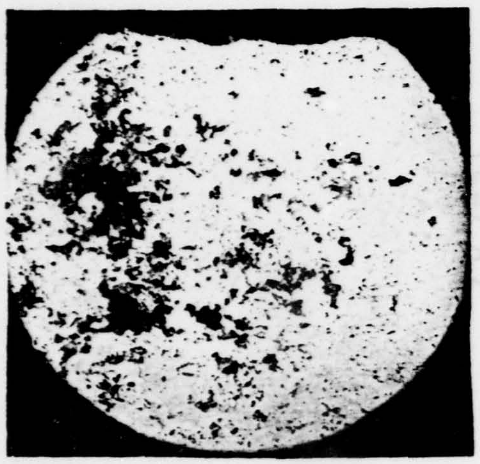
FIGURE 33



Transcrystalline crack (penetration 0·012" (8%t)) and layered intercrystalline corrosion at surface of specimen 24.1.E. This crack typifies many located near the specimen edge at the transverse diameter.

(x 125)

FIGURE 34. Intercrystalline cracking near hole edge (top) at transverse diameter of specimen 13.27.F crack length approx. 0.027"



(a) Minimal surface removal (x63 unetched)

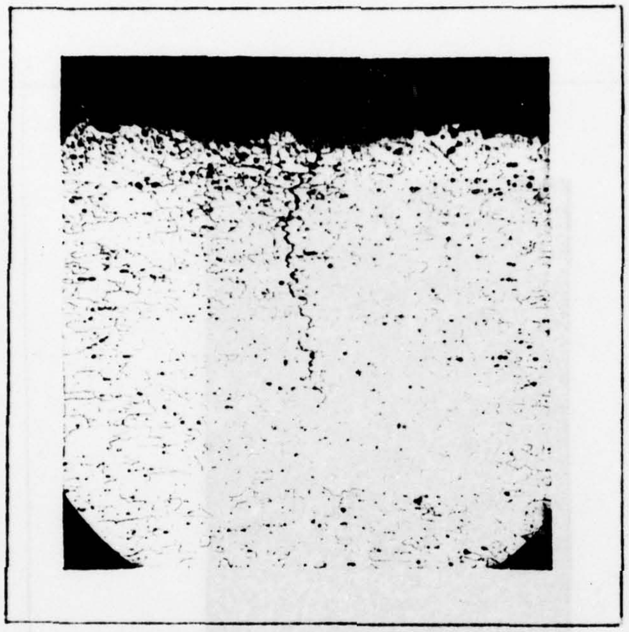
(b) 0.0015" removed from surface (x63 unetched)

FIGURE 35

Mixed mode fracture displayed by specimen 12.12.1
Fatigue propagation from hole joined by longitudinal sheared bridge to SCC at specimen edge (x1)

S.I. N° 8 – EXPOSURE TESTS

FIGURE 36



Intercrystalline crack from surface of specimen 12.11.N (Penetration 0·012" (13%t)). This crack typifies many located near the specimen edge at the transverse diameter

(x 125)

SUPPLEMENTARY INVESTIGATION No.9

AN EXTENSION TO LOWER STRESS LEVELS OF SOME OF THE TESTS DESCRIBED IN STAGE 1

1. INTRODUCTION

This particular supplementary programme of research was undertaken because the results of the Stage 1 tests in the Push Fit Pin - Pin Loaded configuration did not yield endurances much beyond 10^6 cycles, whereas the original intention was to produce endurance curves over a range of 10^4 to 10^7 cycles. Moreover this specific configuration was the one most commonly occurring in practice.

2. GENERAL NOTES

In common with the main research, three sizes of specimen were tested, each with three ratios of pin diameter to width of specimen (d/D). For each combination of size and geometry, tests were made at three or four values of mean stress to produce endurance curves at low alternating stresses, over the range $S_a/f_t = 0.05$ to 0.025. These endurances were then combined with those already obtained in the Stage 1 tests for the range $S_a/f_t = 0.225$ to 0.075, thus giving the required endurance coverage, up to at least 10^7 cycles.

Table 1 gives particulars of the test specimens included in these low stress level tests, together with the reference numbers of the corresponding Figures and Tables in Appendix C of the Stage 1 Report which cover the higher alternating stress levels. It will be noted that in Stage 1 there were no tests done at d/D = 3/8 for the medium and small sizes in the push fit pin - pin loaded case. This was because the tests at d/D = 3/8 were added to the main programme at a late stage, in order to fill in some gaps in the continuity of results, more especially in the large size specimens.

Figure 1 of the present report gives the geometry of the test specimens, and the materials used for the plates and the pins.

During the testing of the specimens, it was found by both organisations concerned (Cambridge University and Short Brothers and Harland) that stability of the testing machine could not be maintained satisfactorily at some of the lowest alternating stress levels, as originally planned, and so the tests at these levels had to be abandoned, or not even attempted. These cases are generally indicated by footnotes on the relevant tables of results. In some other cases the tests at the lowest levels of stress were omitted because sufficiently high endurances had already been achieved at the higher stress levels, which were normally tested first.

3. NOTATION (Units are lb and inches throughout)

For convenience the relevant Notation from the Stage 1 report is repeated below -

d	=	Nominal diameter of hole and pin
D	=	Width of parallel section of test specimen
f_t	=	Average Tensile strength of plate material (from tests)
f_p	=	Average 0.2°/o Proof Stress of plate material (from tests)
K'_t	=	Geometric Stress Concentration factor based on net area of cross section of test specimen
N	=	Endurance
S_m	=	Mean Stress on net area
S_a	=	Alternating Stress on net area associated with S_m
t	=	Thickness of plate specimen

4. RESULTS OF TESTS

These are presented numerically in Tables 2 to 10 and graphically in Figures 2 to 10, each table and corresponding figure being cross referenced, and covering one specimen type as listed in Table 1. Associated with Figures 5, 7, 8 and 10 are Figures 5a, 7a, 8a and 10a respectively, giving alternative endurance curves (see paragraphs 5.1, 5.2 and 5.5).

5. DISCUSSION OF RESULTS

5.1 General

As in Stage 1, fair curves have been drawn through the logarithm mean endurance points for both the original stress levels and the new low stress levels. Where data are limited or scatter is considerable, these curves are shown 'dashed' to indicate their tentative nature.

In Figures 6 and 9 where there are no data from Stage 1 tests, but only the low stress level results, the curves have been drawn with 'dashed' lines because of the lack of higher stress level results and also because the scatter of results is often considerable, including some results which were for unbroken specimens.

In general, the addition of these low stress level tests has enabled the original endurance curves to be extended quite usefully and logically. Comparisons with the Stage 1 curves (references to the appropriate Stage 1 curves are given on each figure) show that uncertainties at the lower ends of the original curves have been clarified and that the curves fair in reasonably well with the low stress level data. There are apparently some exceptions to this feature in which, although a continuous fair curve has been drawn and is possibly acceptable, it is also admissible to draw two separate curves for a given value of S_m/f_t, one for the Stage 1 stress levels and one for the low stress levels, the two curves meeting with a 'kink' or rapid change of slope. In such cases, in the interests of clarity, related alternative Figures 5a, 7a, 8a and 10a have been presented, these being complementary to Figures 5, 7, 8 and 10 respectively.

5.2 Examination of Specimens

In order to be sure that the divergence noted in the previous paragraph was not accidental and just due to excessive scatter, and if justified to establish reasons for the divergence, it was decided to examine in detail the nature of the failures of a number of specimens. Samples were chosen from all three sizes and three variations of geometry, mostly from the regions where there was the greatest divergence from the conventional form of endurance curve, or where one of three endurances at a given stress level was excessively high or excessively low. In addition to inspection by normal vision, a large illuminated magnifying glass and a moderately high powered microscope were used in particular cases to determine the presence or extent of cracks.

Tables 12A, 12B and 12C present the results of this detailed examination, from which the following conclusions have been drawn.

(i) There was considerable evidence of fretting, and multiple cracks were found on many samples, particularly among the medium and small size specimens.

(ii) Several specimens had wide striations, and occasionally there was a step in the formation of the crack.

(iii) One specimen, identification 21.15.L, small size, $d/D = 3/8$, did not show any fretting, but failed asymmetrically at a comparatively low endurance. There was evidence of a suspected flaw in the material, near the edge of the hole, on one side. This specimen was subjected to a high mean stress ($50°/o\ f_t$) and would normally be expected to fail symmetrically as in fact many such specimens did.

(iv) A number of specimens, particularly in the small size, had fine cracks which could only be seen under a high powered microscope. They had not failed completely; therefore had these tests been continued they would have reached higher endurances before complete failure than those recorded in the tables and graphical presentations. They have therefore been specially annotated as unfailed thus U in the tables and +→ in the graphs, and the final choice of the shape of the endurance curve has been modified accordingly.

(v) It would have been helpful if the number of specimens tested at a given stress level had been increased to five or more at the lowest values of alternating stress, because of the greater scatter in this region.

(vi) To sum up, there is some support for an increase of slope of the endurance curves at low alternating stresses, particularly for the small size specimens. It appears to be due to more extensive fretting and to the resulting multiplicity of cracks. This change of slope is not as great as was at first suspected, because a number of tests were discontinued at the onset of a crack and would in fact have survived complete or significant failure until a greater number of cycles had been applied. Consistency of policy in this respect may have been made difficult, because of the calendar time scale involved and to the tendency for unstable operation of the testing machines at low alternating stresses. Having resolved the unexpected variation in behaviour of some of these fatigue specimens at low alternating stresses, the results may now be considered in three groups as follows:

5.3 Configurations which Yield Reliable Continuous Endurance Curves over the Full Stress Range

These are presented on Figures 2, 3 and 4. In each case it will be noted that they are for large size specimens, that the scatter of results at a given stress level is small, and that the fair curves so drawn do not deviate much from the logarithm mean values at each level of alternating stress. Moreover, as a family of curves representing a range of mean stresses they are reasonably spaced, bearing in mind the earlier evidence that variations of mean stress do not produce significant changes of endurance for a given configuration, provided the mean stresses are above 0.25 f_t.

Despite some evidence of heavy fretting and multiple cracks, the large specimen results did not justify a specific change in slope of the endurance curves at the lower alternating stress levels.

5.4 Configurations for which only Low Stress Level Results are Available

Figures 6 and 9 present results which are in this category, and tentative curves have been drawn, partly because of this fact and partly because of the greater scatter which occurs on the medium and small specimens, compared with the large size specimens.

Notice has been taken however of the results of the detailed examination of some of the failures, in order to provide the most reliable slopes of the curves, within the scope of the data available.

5.5 Configurations for which Continuous Endurance Curves over the Full Stress Range can still be Drawn, but for which there is a Region of Divergence, Leading Alternatively to Two Related but Discontinuous Curves, One for the Higher and One for the Lower Group of Alternating Stresses

These configurations are to be found on Figures 5, 7, 8 and 10, i.e. medium and small size specimens, $d/D = 1/4$ and $1/2$. As already stated, alternative endurance curves showing a specific change of slope at some alternating stress level within the range $S_a = 0.04\ f_t$ to $S_a = 0.09\ f_t$ can be drawn and these are given on the complementary Figures 5a, 7a, 8a and 10a respectively. Paragraph 5.2 and Tables 12A, 12B and 12C provide the justification for this alternative presentation, although there is insufficient evidence at some levels of mean stress. Moreover the value of the alternating stress at which the change of slope becomes evident is not constant, but lies within a moderately small range.

The extent of the discontinuity in the endurance curves is greater for the small size specimens than for the medium size.

6. SUMMARY PRESENTATION

In Stage 1, Section 4 paragraph 4.13, a method of presenting all, or nearly all the results for one particular type of loading is given. The method makes use of the fact that it was found that mean stress has but little effect on endurance, for mean stresses of $0.25\ f_t$ and above (chiefly due to resultant plastic flow at the region of maximum stress concentration). Furthermore, by computing and plotting $K_t'S_a$ (or $K_t'S_a/f_t$) instead of S_a (or S_a/f_t) the effect of the more powerful variable d/D (i.e. K_t') is automatically included. The smaller influence of size is covered by plotting endurances for large medium and small sizes with an identifiable code.

In Stage 1, this summary presentation for loaded push fit pins is given on Table 4.11 and plotted on Figure 4.46, and covers an alternating stress range of $S_a = 0.50\ f_t$ to $0.075\ f_t$. The low stress level results can now be added to the Stage 1 results extending the range of S_a from $0.05\ f_t$ to $0.025\ f_t$.

For convenience, Table 4.11 of Stage 1 is reproduced here as Table 11A (leaving out a few loose fit pin results). Table 11B gives similar summary data for the low stress level tests.

Figure 11 of this report presents graphically the data from both Tables 11A and 11B.

A study of Figure 11 shows that, as for the individual endurance curves, so the summary curves of Stage 1 are modified slightly and extended at their lower ends by the further data from the low stress level tests. The form of the extended curves blends well into the Stage 1 curves, although a little "judgement" is required in the region of 10^7 cycles and beyond, because of the considerable number of unbroken specimens, and also because of the difficulty of obtaining reliable results at these low stress levels.

It is to be noted that the grouping of results in this combined presentation has tended to eliminate the rapid changes of slope which were apparent in some of the individual curves, although it is clear that the lower regions of the combined curves are slightly steeper than was at first presumed from the Stage 1 results, supporting to some degree the evidence that the mechanism of failure at the lower stress levels is more predominantly due to fretting and the occurrence of multiple cracks than when tested at the higher alternating stress levels.

The effect of size can be seen by virtue of the plotting code adopted and still indicates that large specimen results tend to lie towards the lower boundary of the band width and the small specimen results towards the upper boundary. In using the band width one should always remember that it is for log mean endurances and so does not embrace the full scatter, which is indicated on the individual curves.

7. COMPARISON WITH RAeS Data Sheet E.05.01

An interesting comparison can be made between Figure 11 of this report and curves derived from Data Sheet E.05.01 (Heywood's general endurance curves for joints, - based on Reference 1).

Because Figure 11 is plotted on the basis of $K_t'S_a$ and not S_a the ordinates of Data Sheet E.05.01 must be multiplied by K_t'. However each joint plotted on that Data Sheet has its own value of K_t' and in the absence of detailed information on this matter, it is suggested that a mean value of $K_t' = 3.0$ might be taken. (The mean value for the Bolted Joint Fatigue Research is actually 2.9).

This leads to the three curves A, B and C corresponding to those of Data Sheet E.05.01, plotted on Figure 11 to represent the mean, the best and the worst of all the joints included in Data Sheet E.05.01. The agreement is obviously good.

Alternatively, the curves of Data Sheet E.05.01 can be plotted directly on any one of Figures 2 to 10 to afford a comparison. Remembering that it is probably more appropriate to compare Heywood's joints with the large size specimens, they have been plotted only in Figures 2, 3 and 4. The comparison is still reasonable and shows in a general way the influence of d/D. It is of interest to note that Reference 1, in analysing the data contained therein, derives a formula for the mean curve "A" which is $S_a = 1500(\frac{1+1000}{\sqrt{N}})$

where S_a = alternating stress in lb/in^2

and N = endurance (cycles to failure)

and, when combined with a mean value for K_t' of 3, provides a reasonable fit to the revised mean curve on Figure 11 representing the present tests.

8. CONCLUSIONS

The extension of the Stage 1 Fatigue Tests to include lower levels of alternating stress has proved to be most useful and illuminating. The resulting summary presentation (Figure 11) provides an adequate endurance band over the full range of 10^4 to 10^7 cycles.

Individual test results for each combination of size and geometry of specimen are shown on Figures 2 to 10 inclusive.

For the large size specimens the endurance curves are clearly defined, without excessive scatter and are conventional at all three values of d/D for alternating stresses down to an average level of $S_a = 0.035\ f_t$. Below levels of this order it was found impossible to stabilise the operation of the testing machine, a 20 Ton Avery Schenck.

For the medium and small size specimens, it was found possible to obtain results down to an alternating stress level of $0.025\ f_t$, but the scatter of results increased with decreasing alternating stress levels. The achievement of lower stress levels was due to the different types and working ranges of the testing machines used for these specimens, - 6 Ton Losenhausen for the medium and 2 Ton Amsler Vibrophore for the small specimens. Reasonable fair and

conventional endurance curves can also be drawn for these two groups of specimens, but on a closer examination of some of them it was noted that a slight divergence was evident in the range of S_a equal to $0.04\ f_t$ to $0.09\ f_t$. A detailed examination of the mode of failure of a number of these specimens indicated the presence of considerable fretting and of multiple cracks in many of them. This would appear to justify increasing the slope locally of some of the endurance curves in the lower alternating stress regions, with an apparent kink at the junction of the two curves for a given mean stress. On the other hand, the examination of the specimens also indicated that a small number of them had only short fine cracks and would have continued to sustain cyclic loading for a further period, and therefore it has been considered justifiable to assume increased endurances and so lessen the lower slopes of the endurance curves in these regions, so that the divergence from the conventional curves is less marked than was at first anticipated, but still worthy of note, particularly for the small size test specimens.

Thus, where these divergencies occurred, alternative rather than replacement curves have been drawn and presented on Figures 5a, 7a, 8a and 10a, corresponding to the more conventional curves of Figures 5, 7, 8 and 10 respectively.

An interesting comparison has been made between the results of these tests and RAeS Data Sheet E.05.01, which is based on Reference 1. Individual comparisons are made on Figures 2, 3 and 4 with the upper limit (B) the mean (A) and the lower limit (C) of all the Aircraft Structural Joints considered by Heywood. A generalised comparison is also made on Figure 11 by assuming a mean value for K_t' of 3. In each case the comparisons are reasonable, the former also showing the influence of d/D.

REFERENCES

1. HEYWOOD, R.B. Correlated Fatigue Data for Aircraft Structural Joints. ARC Current Paper 227, 1956. (Originally RAE Report No.Structures 184).

SUPPLEMENTARY INVESTIGATION No.9

TABLE 1 LOW STRESS LEVEL TESTS PUSH FIT PIN - PIN LOADED

RANGE OF TEST SPECIMENS[+] AND MEAN STRESSES[ø]

Specimen Type	d/D	Endurance curves at percentage Mean Stress Quoted				Stage 1 Figure and Table Reference
(a) Large Specimens - width = 2 in						
1 B 1/2	1/4				15	C.5
1 D 3/4	3/8	50	40	25	15	C.11
1 D 1	1/2				-	C.16
(b) Medium Specimens - width = 1 1/4 in						
2 B 5/16	1/4					C.24
2 D 15/32	3/8	50	40	25	15	*
2 D 5/8	1/2					C.32
(c) Small Specimens - width 3/4 in						
4 B 3/16	1/4				15	C.40
4 D 9/32	3/8	50	40	25	15	*
4 D 3/8	1/2				-	C.48

* No Stage 1 tests were made for these two configurations.

\+ For geometry and material of test specimens, see Figure 1.

ø Mean stresses are quoted as percentages of tensile strength of plate material obtained from static tests - Average Value = 69 400 lb/in^2.

For each mean stress, specimens were tested at three or four alternating stress levels, except in those cases where the resulting stress level was below the working range of the testing machine.

TABLE 2 PUSH FIT PIN - PIN LOADED **Reference Figure 2**

LARGE SIZE SPECIMEN Type 1B 1/2 $d/D = 1/4$ $K_t' = 3.73$

Tested at Short Bros and Harland

Testing Machine - 20 Ton Avery-Schenck, Speed 2000 c.p.m.

Loads to insert pins not greater than 60 lb

Specimen Type	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
34.6.A			230 400	5.361	
35.5.D	50	5	159 600	5.202	156 500
34.5.C			104 200	5.017	
34.6.C			495 600	5.695	
34.6.B	50	4	336 400	5.527	382 000
34.6.D			334 700	5.523	
34.7.B			2 635 600	6.420	
34.7.A	50	3	2 106 100	6.324	2 176 000
* 34.7.C			1 856 000	6.267	
34.8.C			162 000	5.209	
34.7.D	40	5	157 000	5.195	158 000
34.8.B			152 600	5.191	
34.8.D			764 800	5.882	
34.9.C	40	4	502 100	5.701	563 000
34.9.A			464 900	5.656	
35.4.A			2 033 600	6.308	
34.9.D	40	3	1 882 400	6.274	1 853 000
34.4.B			1 661 100	6.220	
35.5.A			846 300	5.927	
35.4.D	25	4	823 300	5.915	751 500
35.4.C			609 300	5.785	
35.5.C			1 878 700	6.272	
35.5.B	25	3	1 637 200	6.213	1 709 000
35.5.D			1 625 100	6.210	
* 35.6.B			1 994 500	6.300	
* 35.6.A	15	4	1 534 900	6.190	1 301 000
* 35.6.C			719 300	5.855	
35.7.A			3 595 900	6.555	
35.7.B	15	3	2 060 900	6.313	2 396 000
35.6.D			1 855 600	6.268	

NB Alternating stresses lower than $3^{o}/o$ f_t were outside the satisfactory working range of the testing machine.

* Specimen examined for nature of failure, see Table 12a

SUPPLEMENTARY INVESTIGATION No.9

TABLE 3 PUSH FIT PIN - PIN LOADED — Reference Figure 3

LARGE SIZE SPECIMEN Type 1 D 3/4 d/D = 3/8 $K_t' = 2.72$

Tested at Short Brothers and Harland

Testing Machine - 20 Ton Avery-Schenck, Speed 2000 c.p.m.

Loads to insert pins range from 36 lb to 295 lb

Specimen Identity	Stress Levels* Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
4.8.D 4.7.D 4.7.C	50	5	282 500 200 200 139 900	5.450 5.301 5.145	199 200
4.12.D 4.12.E 4.10.D	50	4	1 167 400 1 049 900 715 400	6.066 6.020 5.854	957 200
⁑ 4.12.A 4.13.D 4.14.E	50	3.5	1 508 600 1 465 200 1 240 500	6.178 6.166 6.095	1 399 600
5.4.D 5.2.D 5.4.B	40	5	305 000 283 100 245 700	5.485 5.452 5.390	277 000
5.5.D 5.11.D 5.6.D	40	4	1 262 900 1 145 500 417 000	6.100 6.059 5.620	845 500
5.6.E	40	3.5*	1 589 000	6.200	1 589 000
6.1.C 5.6.B 5.11.C	25	5	738 800 659 800 490 300	5.868 5.819 5.691	620 600
⁑ 6.1.E ⁑ 6.6.D ⁑ 6.7.C	25	4	2 281 800 537 600 525 400	6.357 5.729 5.720	863 800
6.8.A 6.7.D 6.7.E	15	5	739 500 729 800 586 100	5.825 5.862 5.767	681 400
6.8.B 6.9.D 6.8.E	15	4	1 645 700 1 541 200 1 520 500	6.216 6.188 6.181	1 568 600

*NB It was found to be difficult to obtain results at an alternating stress level of 3.5°/o f_t (possible error ±22°/o) and so further testing at alternating stress levels at 3.5°/o f_t and below was discontinued.

⁑ Specimen examined for nature of failure, see Table 12a

TABLE 4 PUSH FIT PIN - PIN LOADED **Reference Figure 4**

LARGE SIZE SPECIMEN Type 1.D.1 $d/D = 1/2$ $K_t' = 2.22$

Tested at Short Brothers and Harland

Testing Machine - 20 Ton Avery Schenck, Speed 2000 c.p.m.

Loads to insert pins range from 100 lb to 300 lb

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
12.2.C			906 700	5.955	
12.2.D	50	5	798 800	5.900	690 000
# 12.2.A			453 500	5.656	
12.10.A			1 805 100	6.257	
12.3.E	50	4*	1 261 000	6.101	1 382 000
12.3.C			1 161 800	6.065	
# 12.11.B			1 051 700	6.020	
12.11.D	40	5*	731 000	5.864	783 000
12.11.A			624 000	5.795	
# 12.12.A			1 008 000	6.003	
12.11.E	25	5*	732 000	5.865	793 000
12.12.B			674 500	5.289	

*NB Difficulties in maintaining stable operation of testing machine at lower stress levels led to their abandonment.

\# Specimen examined for nature of failure, see Table 12a.

TABLE 5 SUPPLEMENTARY INVESTIGATION No.9
PUSH FIT PIN - PIN LOADED

Reference Figure 5

MEDIUM SIZE SPECIMEN Type 2 B 5/16 d/D = 1/4 $K_t' = 3.73$

Tested at Cambridge University

Testing Machine - 6 Ton Losenhausen, Speed 1500 c.p.m.

Loads to insert pins not known

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
* 24.18.E			988 770	5.995	
25.1.B	50	5	742 520	5.870	599 000
25.1.A			290 860	5.464	
* 25.1.E			2 409 190	6.383	
25.1.C	50	4	785 000	5.895	918 000
25.2.A			403 410	5.605	
25.2.D			7 182 000	6.855	
25.2.E	50	3	4 261 000	6.630	4 325 000
25.2.B			2 673 100	6.426	
25.5.D			7 949 700	6.875	
25.3.C	50	2.5	7 342 700	6.865	6 200 000
* 25.3.A			4 360 100	6.640	
25.6.B			456 140	5.660	
25.5.E	40	5	433 040	5.636	429 000
25.6.A			401 120	5.602	
25.7.B			1 655 260	6.218	
25.8.A	40	4	1 068 240	6.029	1 075 000
25.7.A			701 700	5.846	
* 25.8.D			8 440 000	6.926	
25.9.A	40	3	3 027 000	6.480	4 280 000
* 25.8.C			2 445 850	6.337	
25.10.B			10 501 000	7.020	
25.9.E	40	2.5	6 490 000	6.810	6 960 000
25.10.A			5 028 000	6.700	
* 25.11.E			9 598 000	6.980	
* 25.11.B	25	4	4 754 900	6.676	5 530 000
25.10.D			3 736 050	6.570	
25.14.B			7 167 000	6.853	
25.13.A	25	3	6 776 330	6.830	4 960 000
* 25.14.A			2 533 000	6.402	
25.15.A			14 812 000U	7.170U	
25.14.D	25	2.5	14 791 000U	7.170U	>14 050 000
25.14.C			12 676 000U	7.102U	
25.15.E			3 865 730	6.587	
25.15.B	15	4	2 625 550	6.418	2 855 000
25.15.D			2 297 850	6.360	
25.16.C			10 476 000	7.020	
25.16.B	15	3	4 142 000	6.615	4 780 000
25.16.A			2 543 880	6.404	
25.17.A			14 828 000U	7.170U	
25.16.E	15	2.5	14 813 000U	7.170U	>14 816 000
25.16.D			14 808 000U	7.170U	

U Denotes unbroken specimen

* Specimen examined for nature of failure, see Table 12b

TABLE 6 PUSH FIT - PIN LOADED

Reference Figure 6

MEDIUM SIZE SPECIMEN Type 2 D 15/32 $d/D = 3/8$ $K_t' = 2.72$

Tested at Cambridge University

Testing Machine - 6 Ton Losenhausen, Speed 1500 c.p.m.

Loads to insert pins not known.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
9.1.C 9.1.A 9.1.B	50	5	1 738 900 854 990 427 800	6.240 5.932 5.630	860 000
9.1.D 9.1.E 9.2.A	48.5 ✱	4	4 061 890 2 078 420 1 107 130	6.609 6.318 6.045	2 115 000
9.2.D 9.2.B # 9.2.E	50	3	30 044 000U 12 350 000 3 606 840	7.482U 7.091 6.556	>11 050 000
# 9.3.A 9.2.C 9.3.B	50	2.5	28 548 000U 6 108 480 4 565 500	7.455U 6.786 6.659	>9 250 000
9.3.D 9.3.E 9.3.C	40	5	1 838 920 1 019 320 651 550	6.263 6.009 5.813	1 070 000
9.4.C 9.4.A 9.4.B	40	4	3 995 070 1 949 430 1 132 890	6.600 6.290 6.055	2 065 000
9.5.A 9.4.E 9.4.D	40	2.5	23 201 000U 21 119 000U 20 910 000U	7.365U 7.324U 7.320U	>21 700 000
9.5.C 9.5.D 9.5.B	25	5	1 042 400 984 740 811 830	6.018 5.992 5.908	938 000
9.5.E 9.6.A 9.6.B	25	4	22 091 000U 17 169 000 14 416 000	7.343U 7.233 7.160	>17 600 000
9.6.E 9.6.D 9.6.C	25	2.5	25 232 500U 21 870 000U 21 071 000U	7.401U 7.340U 7.323U	>22 600 000
# 9.7.B # 9.7.C # 9.7.A	15	5	21 465 000U 2 000 000 1 257 000	7.330U 6.301 6.099	>3 790 000

✱ Inadvertently tested at 48.5°/o f_t instead of at 50°/o f_t, but error considered negligible.

U Denotes unbroken specimen

Specimen examined for nature of failure, see Table 12b

SUPPLEMENTARY INVESTIGATION No.9

TABLE 7 PUSH FIT PIN - PIN LOADED Reference Figure 7

MEDIUM SIZE SPECIMEN Type 2 D 5/8 d/D = 1/2 $K_t' = 2.22$

Tested at Cambridge University

Testing Machine - 6 Ton Losenhausen, Speed 1500 c.p.m.

Loads to insert pins not known.

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
5.3.E 5.7.B 5.3.C	50	5	2 136 000 1 280 750 956 190	6.328 6.107 5.980	1 275 000
5.9.C 5.8.D 5.9.E	50	4	4 301 710 3 135 820 1 263 390	6.634 6.496 6.100	2 570 000
5.11.E 5.10.E 5.10.A	50	2.5	14 822 000U 14 753 000U 12 437 000U	7.170U 7.168U 7.095U	>13 950 000
# 5.15.E # 5.16.B # 5.15.C	40	5	10 560 000U 2 445 330 2 398 470	7.024U 6.386 6.378	>3 950 000
5.17.E 5.17.D # 5.18.A	40	4	10 072 000U 8 778 000 3 641 600	7.004U 6.943 6.560	>6 850 000
5.20.B 6.1.E 5.18.E	40	2.5	12 614 000U 10 877 000U 10 592 000U	7.100U 7.036U 7.025U	>11 300 000
6.3.D 6.2.A	25	5	1 851 620 1 125 440	6.256 6.050	1 425 000
6.5.E 6.8.D	15	5	3 935 950 3 698 440	6.595 6.568	3 810 000

U Denotes unbroken specimens

\# Specimen examined for nature of failure, see Table 12b

TABLE 8 PUSH FIT PIN - PIN LOADED Reference Figure 8

SMALL SIZE SPECIMEN Type 4 B13/16 d/D = 1/4 $K_t' = 3.73$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins not known

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
	S_m	$\pm S_a$			
1.7.G			1 687 000	6.227	
1.6.B	50	5	1 427 000	6.155	1 420 000
1.6.C			1 191 000	6.075	
# 1.7.J			7 957 000Ⓤ	6.900Ⓤ	
1.8.A	50	4	1 739 000	6.239	>2 600 000
# 1.8.E			1 266 000	6.102	
1.9.G			4 076 000	6.610	
1.8.F	50	3	4.048 000	6.606	>3 880 000
# 1.9.C			3 572 000Ⓤ	6.552Ⓤ	
1.14.A			334 000	5.522	
1.13.I	44.5 ϕ	5.5 ϕ	258 000	5.410	232 000
1.14.C			146 000	5.164	
# 1.11.H			1 676 000Ⓤ	6.223Ⓤ	
# 1.11.F	40	4	1 500 000	6.175	>1 408 000
1.13.H			1 115 000	6.046	
1.15.F			11 790 000U	7.070U	
1.14.J	44 +	3	11 081 000U	7.045U	>11 200 000
1.14.I			10 730 000U	7.030U	
# 1.15.J			14 538 000	7.160	
1.17.E	25	4	6 037 000	6.782	5 100 000
# 1.18.F			1 533 000	6.185	
1.20.C			14 788 000	7.169	
1.18.H	25	3	9 758 000	6.990	9 700 000
1.18.I			6 300 000	6.800	
1.22.B			32 870 000U	7.515U	
1.21.H	25	2.5	13 140 000U	7.118U	>17 260 000
1.21.G			11 866 000U	7.075U	
1.22.J			12 762 000	7.105	
2.2.C	15	4	3 284 000	6.515	3 790 000
1.22.C			1 306 000	6.115	
2.3.I			15 898 000	7.200	
2.3.C	15	3	13 730 000	7.138	>9 250 000
# 2.3.D			3 648 000Ⓤ	6.560Ⓤ	
2.4.F			13 876 000U	7.142U	
2.4.D	15	2.5	13 560 000U	7.132U	>12 580 000
2.4.H			10 573 000U	7.023U	

ϕ Should have been tested at 40^o/o $\pm 5^o$/o but will be plotted as 40^o/o $\pm 5.5^o$/o with negligible error (see Stage 1 results for effect of mean stress)

\+ Should have been tested at 40^o/o $\pm 3^o$/o but will be plotted as 40^o/o $\pm 3^o$/o with negligible error.

U Denotes unbroken specimen

Ⓤ Denotes specimen found "unbroken" on detail examination

\# Specimen examined for nature of failure, see Table 12C

SUPPLEMENTARY INVESTIGATION No.9

TABLE 9 PUSH FIT PIN - PIN LOADED   Reference Figure 9

SMALL SIZE SPECIMEN Type 4 D 9/32 d/D = 3/8 $K'_t = 2.72$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins not known.

	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
		S_m	$\pm S_a$			
	21.15.F			946 000	5.976	
	21.15.D	50	5	661 000	5.820	717 000
	21.15.B			590 000	5.770	
	21.15.G			3 193 000	6.504	
	21.15.H	50	4	2 365 000	6.368	2 470 000
	21.15.J			1 775 000	6.249	
#	21.15.M			38 072 000U	7.580U	
	21.15.N	50	2.5	7 570 000	6.878	>7 650 000
#	21.15.L			1 577 000	6.191	
#	21.15.O			3 700 000	6.568	
	21.16.B	40	5	858 000	5.932	1 375 000
	21.16.A			820 000	5.913	
	21.16.C			4 244 000	6.627	
	21.16.G	40	4	1 752 000	6.243	2 180 000
	21.16.H			1 398 000	6.194	
	21.16.M			21 693 000U	7.336U	
	21.16.J	40	2.5	15 798 000U	7.197U	>11 550 000
#	21.16.K			4 472 000U	6.650U	
	21.17.L			5 012 000	6.700	
	21.17.J	25	5	2 103 000	6.323	2 120 000
#	21.17.A			923 000	5.949	
	21.17.N			4 706 000	6.673	
	21.18.A	25	4	3 833 000	6.583	2 410 000
#	21.17.O			778 000	5.890	
	21.18.C			21 224 000U	7.325U	
	21.18.B	25	2.5	17 441 000	7.240	>13 400 000
	21.18.D			6 572 000	6.817	
	21.18.E			9 018 000	6.995	
#	21.18.F	15	5	106 000	5.025	440 000
#	21.18.G			89 000	4.950	

U Denotes unbroken specimen

U Denotes specimen found "unbroken" on detail examination

\# Specimen examined for nature of failure, see Table 12C

TABLE 10 PUSH FIT PIN - PIN LOADED Reference Figure 10

SMALL SIZE SPECIMEN Type 4 D 3/8 $d/D = 1/2$ $K'_t = 2.22$

Tested at Cambridge University

Testing Machine - 2 Ton Amsler Vibrophore, Speed 7500 c.p.m.

Loads to insert pins not known

	Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Logarithm Cycles to Failure	Geometric Mean Cycles
		S_m	$\pm S_a$			
*	23.7.G	50	5	1 503 000U (circled)	6.177U (circled)	>742 000
	23.7.L			966 000	5.983	
*	23.7.H			282 000	5.450	
	23.7.M	50	4	2 197 000	6.341	1 440 000
	23.7.N			1 666 000	6.222	
	23.8.B			1 610 000	6.206	
*	23.8.A			722 000	5.858	
	23.8.H	50	2.5	33 022 000U	7.521U	>31 400 000
	23.8.C			31 398 000	7.495	
	23.8.D			29 649 000U	7.472U	
*	23.8.I	40	5	4 251 000	6.628	3 450 000
	23.8.J			2 399 000	6.380	
	23.8.K			2 024 000	6.305	
	23.8.L	40	4	21 335 000U	7.328U	>10 650 000
	23.9.C			20 278 000U	7.306U	
*	23.9.K			2 740 000	6.436	
*	23.10.C	40	2.5	33 038 000U	7.520U	>28 500 000
	23.9.L			32 689 000U	7.514U	
	23.10.F			27 844 000	7.445	
	23.10.H			21 667 000U	7.336U	
*	23.10.O	25	5	26 620 000	7.425	7 070 000
	23.10.E			6 438 000	6.808	
	23.10.N			2 086 000	6.319	
	23.11.F	25	4	21 607 000U	7.335U	>12 580 000
	23.11.K			7 320 000	6.864	

U Denotes unbroken specimen

U (circled) Denotes specimen found "unbroken" on detail examination

* Specimen examined for nature of failure, see Table 12C

SUPPLEMENTARY INVESTIGATION No.9

TABLE 11A LOGARITHM MEAN ENDURANCES FOR PUSH FIT PIN - PIN LOADED

(Reference Figure 11)

STAGE 1 ALTERNATING STRESS LEVELS (Reference Table 4.11 of Stage 1 Report)

S_m/f_t = 0.50, 0.40 and 0.25 Combined

d/D = 1/4, 3/8 and 1/2 represented by

K'_t = 3.73, 2.72 and 2.22 respectively.

LARGE, MEDIUM AND SMALL SPECIMENS

SUMMARY PRESENTATION

			Geometry	d/D=1/4 K'_t=3.73			d/D=3/8 K'_t=2.72			d/D=1/2 K'_t=2.22		
			Size	L	M	S	L	M	S	L	M	S
			Reference Table	C.5	C.24	C.40	C.11	-	-	C.16	C.32	C.48
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a									
0.225	1/4	0.840	58 200	4 800	6 600	14 200						
	3/8	0.615	42 500				10 500	-	-			
	1/2	0.500	34 700							13 800	28 800	37 200
0.15	1/4	0.560	38 800	27 000	13 800	25 200						
	3/8	0.410	28 500				20 000	-	-			
	1/2	0.333	23 100							25 700	71 000	155 000
0.10	1/4	0.373	25 900	21 400	39 000	52 500						
	3/8	0.272	18 900				45 800					
	1/2	0.222	15 400							52 500	214 000	678 000+
0.075	1/4	0.280	19 400	45 700	72 400	182 000						
	3/8	0.205	14 200				110 000	-	-			
	1/2	0.166	11 500							148 000	385 000	1 260 000+

\+ Signifies UNBROKEN for one or more of nine specimens.

SUPPLEMENTARY INVESTIGATION No.9

TABLE 11B LOGARITHM ENDURANCES FOR PUSH FIT PIN - PIN LOADED

(Reference Figure 11)

STAGE 2 LOW ALTERNATING STRESS LEVELS

S_m/f_t = 0.50, 0.40 and 0.25 Combined

d/D = 1/4, 3/8 and 1/2 represented by

K'_t = 3.73, 2.72 and 2.22 respectively.

LARGE, MEDIUM AND SMALL SIZE SPECIMENS

SUMMARY PRESENTATION

			Geometry	d/D=1/4	K'_t=3.73		d/D=3/8	K'_t=2.72		d/D=1/2	K'_t=2.22	
			Size	L	M	S	L	M	S	L	M	S
			Reference Table	2	5	8	3	6	9	4	7	10
S_a/f_t	d/D	K'_tS_a/f_t	K'_tS_a									
0.05	1/4	0.187	13 000	155 000	503 000	577 000⊕						
	3/8	0.136	9 450				324 000	910 000	1 260 000			
	1/2	0.111	7 700							742 000	2 045 000	2 190 000+
0.04	1/4	0.149	10 350	538 000	1 740 000	2 630 000						
	3/8	0.109	7 550				872 000	4 270 000+	2 350 000			
	1/2	0.089	6 200							1 380 000	4 180 000+	4 470 000+
0.03	1/4	0.112	7 800	1 910 000	4 370 000	5 750 000+						
	3/8	0.082	5 700				1 445 000ɸ	10 450 000+	-			
	1/2	0.067	4 650							-	-	-
0.025	1/4	0.0935	6 500	-	8 510 000+	17 000 000						
	3/8	0.068	4 700				-	16 600 000+	10 450 000			
	1/2	0.055	3 850						-	-	12 300 000+	29 600 000+

\+ Signifies UNBROKEN for one or more of nine specimens.

⊕ Average S_a/f_t = 0.0525 for this group only.

ɸ S_a/f_t = 0.035 for this group only.

TABLE 12A SUPPLEMENTARY INVESTIGATION No.9

LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

LARGE SPECIMENS EXAMINED FOR NATURE OF FAILURE

Specimen Identity	Stress Levels Percentage f_t		Cycles to Failure	Failure Details
	S_m	$\pm S_a$		
Type 1 B 1/2 d/D = 1/4				
34.7.C	50	3	1 856 000	Heavy fretting and multiple cracks on both sides of hole.
35.6.B	15	4	1 994 500	Moderate fretting, stepped crack on one side.
35.6.A	15	4	1 534 900	Moderate fretting, stepped crack on one side.
35.6.C	15	4	719 300	Very heavy fretting and multiple cracks.
Type 1 D 3/4 d/D = 3/8				
4.12.A	50	3.5	1 508 600	Multiple cracks on both sides.
6.1.E	25	4	2 281 800	Multiple cracks, wide striations.
6.6.D	25	4	537 600	Multiple cracks, only slightly different from 6.1.E.
6.7.C	25	4	525 400	Multiple cracks, only slightly different from 6.1.E.
Type 1 D 1 d/D = 1/2				
12.2.A	50	5	453 500	Little fretting but poor finish at hole edges.
12.11.B	40	5	731 000	Multiple cracks.
12.12.A	25	5	1 051 700	Multiple cracks.

TABLE 12B LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

MEDIUM SPECIMENS EXAMINED FOR NATURE OF FAILURE

Specimen Identity	Stress Levels Percentage f_t S_m	$\pm S_a$	Cycles to Failure	Failure Details
Type 2 B 5/16 d/D = 1/4				
24.18.E	50	5	988 770	Heavy fretting both sides, and symmetric failure.
25.1.E		4	2 409 190	
25.3.A		2.5	4 360 100	Heavy fretting, multiple cracks on both sides.
25.8.D	40	3	8 440 000	Multiple cracks, heavy fretting one side, moderate fretting on opposite side.
25.8.C			2 445 850	Heavy fretting both sides, symmetric failure.
25.11.E	25	4	9 598 000	Multiple cracks one side with wide striations; opposite side almost all static failure.
25.11.B			4 754 900	Heavy fretting both sides; wide striations one side, static failure on opposite side.
25.14.A	25	3	2 533 000	Multiple cracks one side only - asymmetric failure.
Type 2 D 15/32 d/D = 3/8				
9.2.E	50	3	3 606 840	Multiple cracks one side only, static failure on opposite side.
9.3.A	50	2.5	28 548 000U	Only slight fretting, no failure.
9.7.B	15	5	21 465 000U	Slight fretting, no failure.
9.7.C			2 000 000	Fretting one side only, static failure on opposite side.
9.7.A			1 257 000	Excessive fretting, fatigue failure both sides.
Type 2 D 5/8 d/D = 1/2				
5.15.E	40	5	10 560 000U	No fretting, unfailed.
5.16.B			2 445 330	Fretting one side only, asymmetric failure.
5.15.C			2 398 470	Fretting on both sides.
5.18.A	40	4	3 641 600	Failure on one side only, small crack on opposite side.

U Denotes unbroken

TABLE 12C SUPPLEMENTARY INVESTIGATION No.9
LOW STRESS LEVEL TESTS
PUSH FIT PIN - PIN LOADED
SMALL SPECIMENS EXAMINED FOR NATURE OF FAILURE

Specimen Identity	Stress Levels Percentage f_t S_m	$\pm S_a$	Cycles to Failure	Failure Details
Type 4 B1 3/16	d/D = 1/4			
1.7.J	50	4	7 957 000 U	Slight crack, no failure.
1.8.E	50	4	1 266 000	Slight fretting, symmetric failure.
1.9.C	50	3	3 572 000 U	Very small crack one side, no failure.
1.11.H	40	4	1 676 000 U	Slight crack, no failure.
1.11.F	40	4	1 500 000	Slight fretting; crack one side, opposite side failed.
1.15.J	25	4	14 538 000	Slight fretting, asymmetric failure.
1.18.F	25	4	1 533 000	Some fretting, crack one side, opposite side failed.
2.3.D	15	3	3 648 000 U	Very small crack one side, no failure.
Type 4 D 9/32	d/D = 3/8			
21.15.M	50	2.5	38 072 000U	No fretting, very good quality hole.
21.15.L	50	2.5	1 577 000	No fretting, possible flow in material just in from hole; asymmetric failure.
21.15.O	40	5	3 700 000	No fretting, small crack one side only - good quality hole.
21.16.K	40	2.5	4 472 000 U	Slight crack, no failure.
21.17.A	25	5	923 000	Moderate fretting one side, static failure on opposite side.
21.17.O	25	4	778 000	Narrow striations one side, static failure on other side.
21.18.F	15	5	106 000	Slight fretting and crack on one side only.
21.18.G	15	5	89 000	Slight fretting and crack on one side only.
Type 4 D 3/8	d/D = 1/2			
23.7.G	50	5	1 503 000 U	Little fretting, small crack both sides but no failure.
23.7.H	50	5	282 000	Fretting one side only, asymmetric failure.
23.8.A	50	4	722 000	Fretting one side only, asymmetric failure.
23.8.I	40	5	4 251 000	Fretting one side only, asymmetric failure.
23.9.K	40	4	2 740 000	Fretting one side only, asymmetric failure.
23.10.C	40	2.5	33 038 000U	Slight fretting only, no failure.
23.10.O	25	5	26 620 000	Negligible fretting, but specimen did fail.

U Denotes unbroken

U Denotes specimen found "unbroken" on detailed examination.

S.I. No 9 – LOW STRESS LEVEL TESTS

PUSH FIT PIN – PIN LOADED

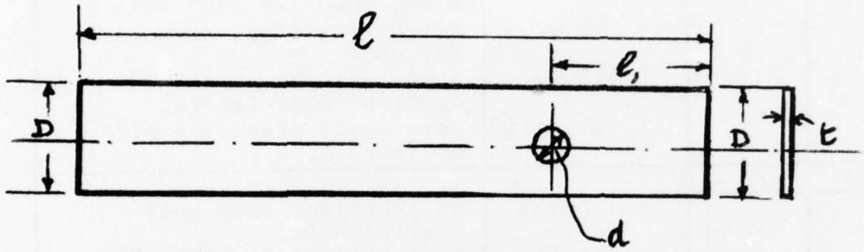
FIGURE 1

DETAILS OF SPECIMENS

PLATES

SHAPE B FOR

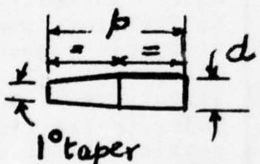
$d/D = 1/4$ (ALSO B_1)



SHAPE D FOR

$d/D = 3/8$ & $1/2$

PINS



DIMENSIONS (INCHES) & MATERIALS

PLATES - MATERIAL BS L71										PINS Material BS S94	
LARGE SIZE											
Type	Shape	d	D	d/D	w	l	l_1	l_2	t	d	p
1 B 1/2	B	1/2	2	1/4	3	12 1/8	3	3 5/8	1/4	1/2	2
1 D 3/4	D	3/4	2	3/8	-	12 1/8	3	-	1/4	3/4	2
1 D 1	D	1	2	1/2	-	12 1/8	3	-	1/4	1	2
MEDIUM SIZE											
2 B 5/16	B	5/16	1 1/4	1/4	1 1/2	6 17/32	1 7/8	1 3/4	5/32	5/16	1 1/2
2 D 15/32	D	15/32	1 1/4	3/8	-	7 5/32	1 7/8	-	5/32	15/32	1 1/2
2 D 5/8	D	5/8	1 1/4	1/2	-	7 5/32	1 7/8	-	5/32	5/8	1 1/2
SMALL SIZE											
4 B1 3/16	B	3/16	3/4	1/4	1 1/8	5	1 1/8	2	3/32	3/16	1
4 D 9/32	D	9/32	3/4	3/8	-	5	1 1/8	-	3/32	9/32	1
4 D 3/8	D	3/8	3/4	1/2	-	5	1 1/8	-	3/32	3/8	1

NOTES

(i) Hole diameter drilled to a tolerance of ±0.003 in. and pin diameter made to even closer tolerances. By means of selective assembly a final push fit to a "clearance" of ±0.003 in. was achieved.

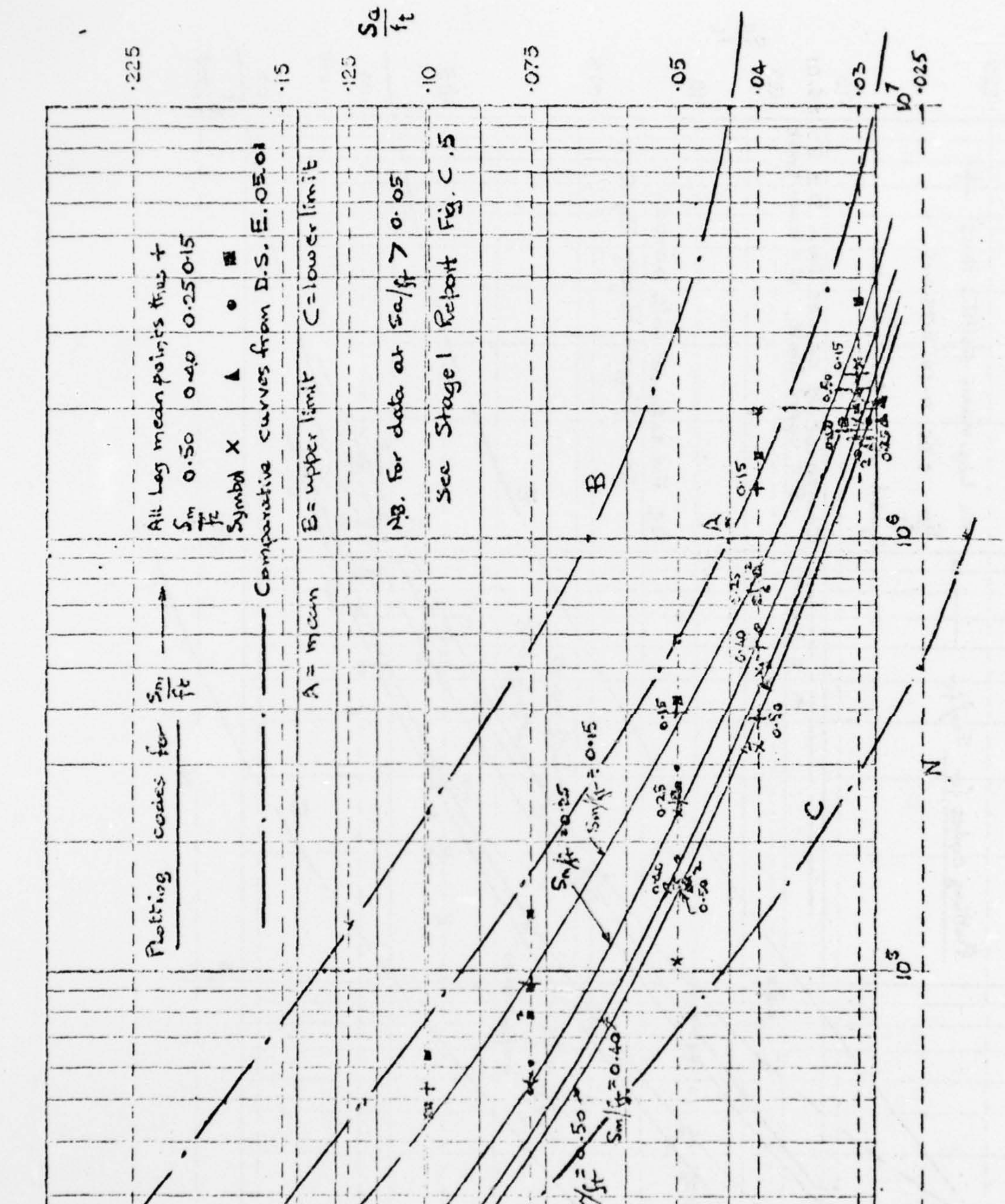
(ii) Load applied to pin in double shear by separate side plates, and specimens tested in Fatigue Testing Machines, as follows:-
Large Specimens - 20 Ton Schenck,
Medium Specimens - 6 Ton Losenhausen and
Small Specimens - 2 Ton Amsler.

SI. Nº 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

Ref TABLE 2

FIG 2 LARGE SPECIMENS - TYPE 1 B ½ $d/D = 1/4$ $K'_t = 3.73$

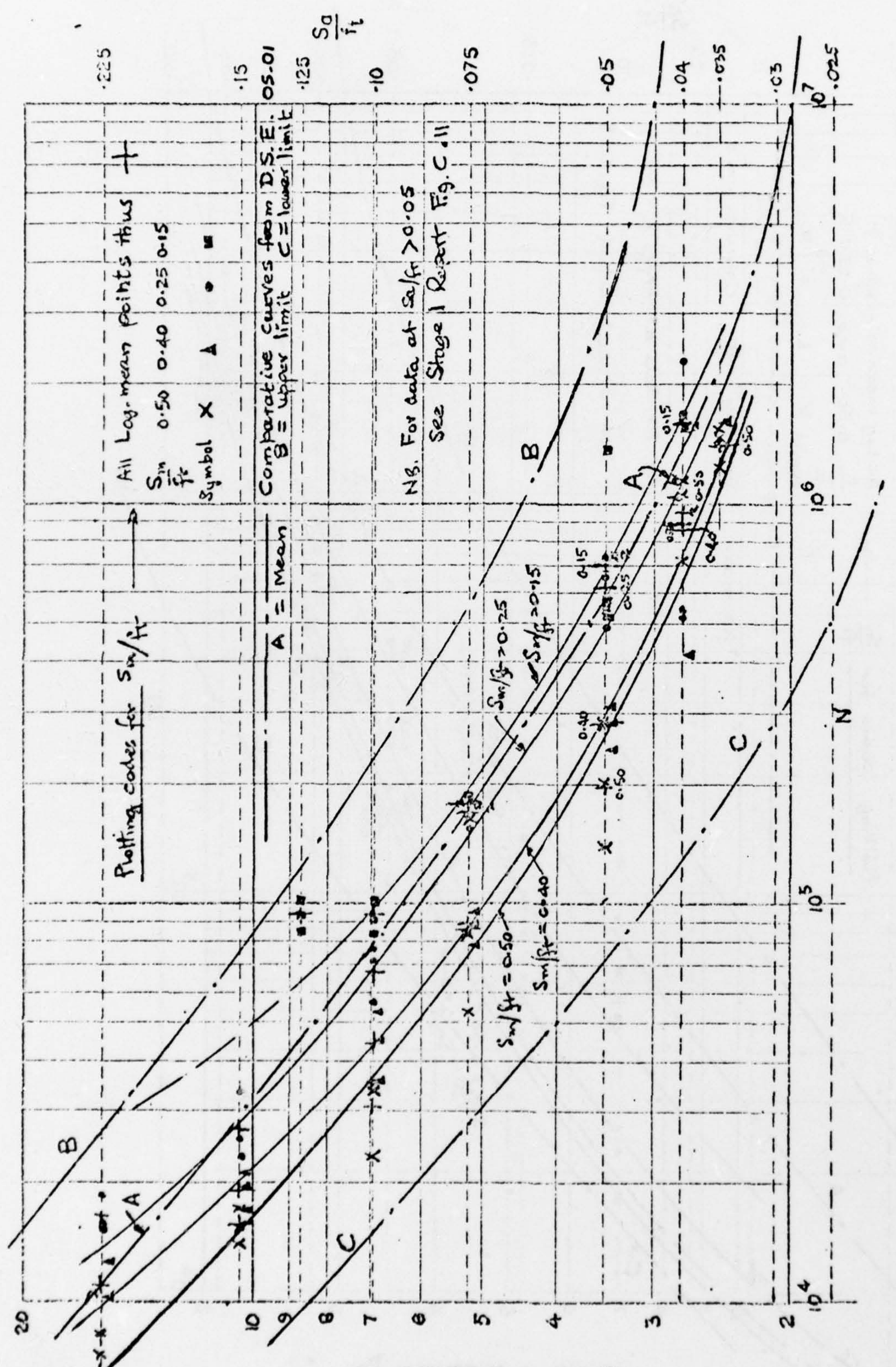


S1. No 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

Ref. TABLE 3

FIG 3. LARGE SPECIMENS - TYPE 1 D 3/4 $d/D = 3/8$ $K_t' = 2.72$

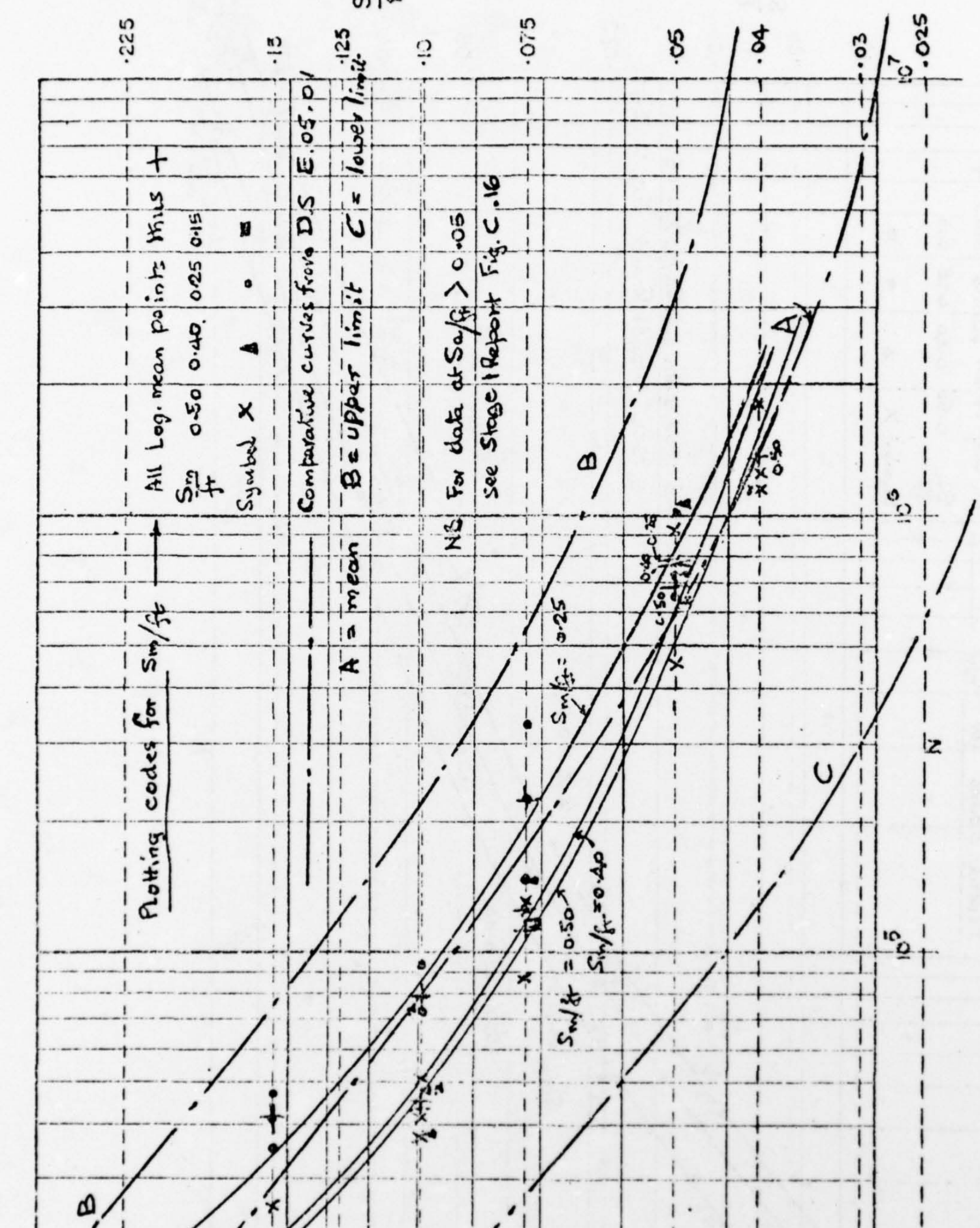


S1. No 9 – LOW STRESS LEVEL TESTS

PUSH FIT PIN – PIN LOADED

Ref. TABLE 4.

FIG 4 LARGE SPECIMENS – TYPE 1.D.1 $d/D = 1/2$ $K_t' = 2.22$



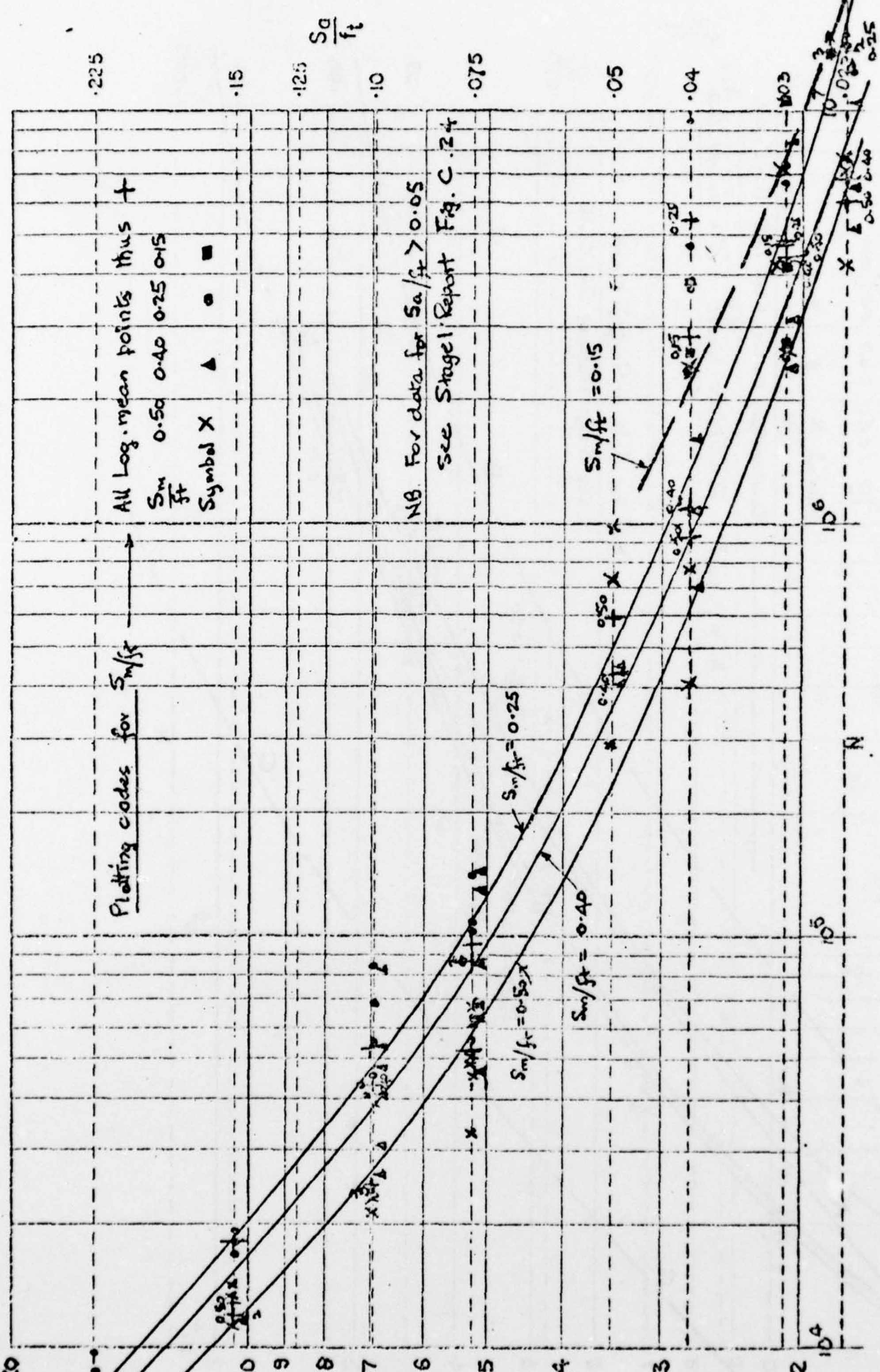
13C

S.I. No 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

Ref. TABLE 5

FIG. 5 MEDIUM SPECIMENS - TYPE 2B 5/16 $d/D = 1/4$ $K'_t = 3.73$

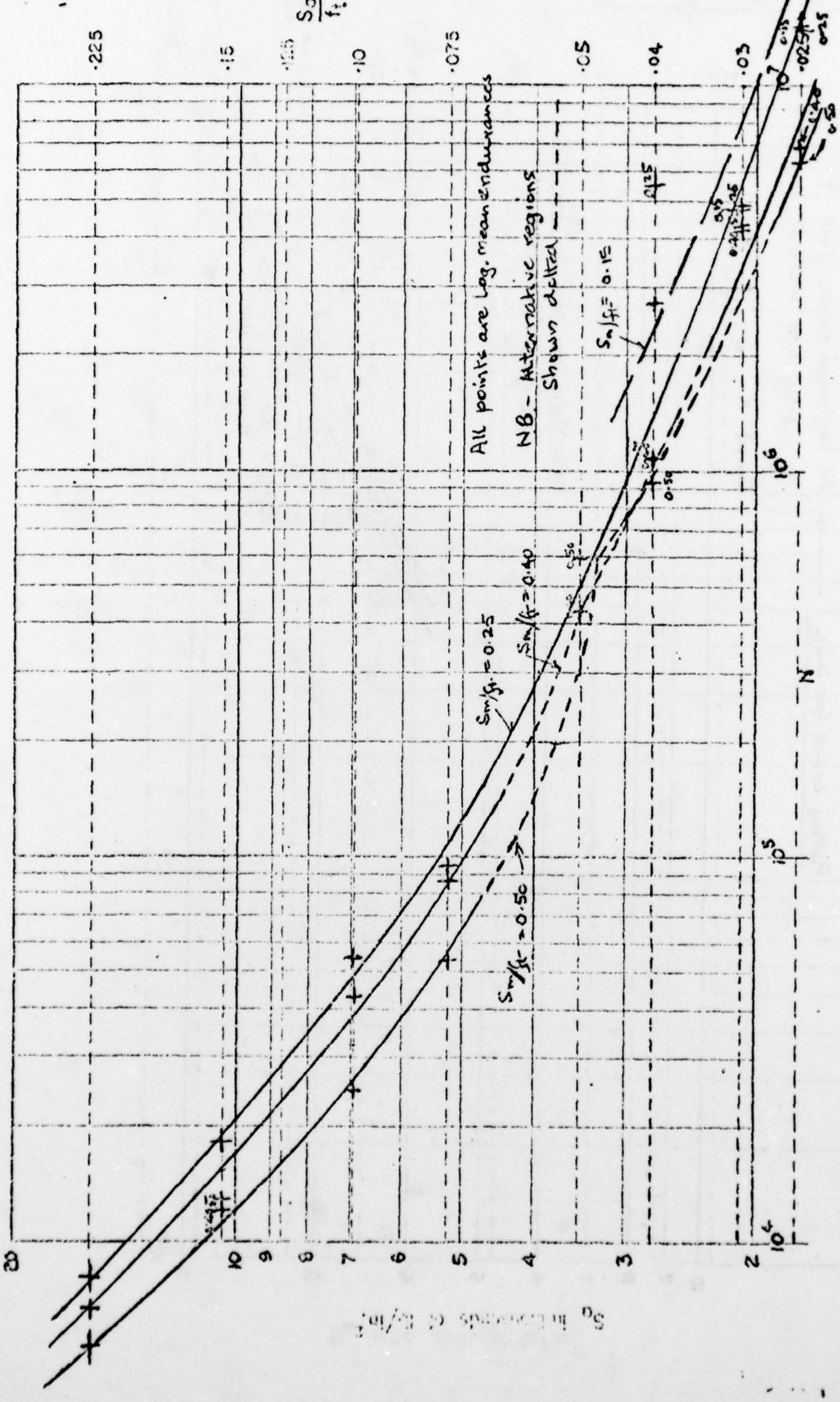


SI. No 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

FIG 5a - MEDIUM SPECIMENS - TYPE 2B 5/16 $d/D = 1/4$ $K_t' = 3.73$

ALTERNATIVE ENDURANCE CURVES (c.f. Fig 5)

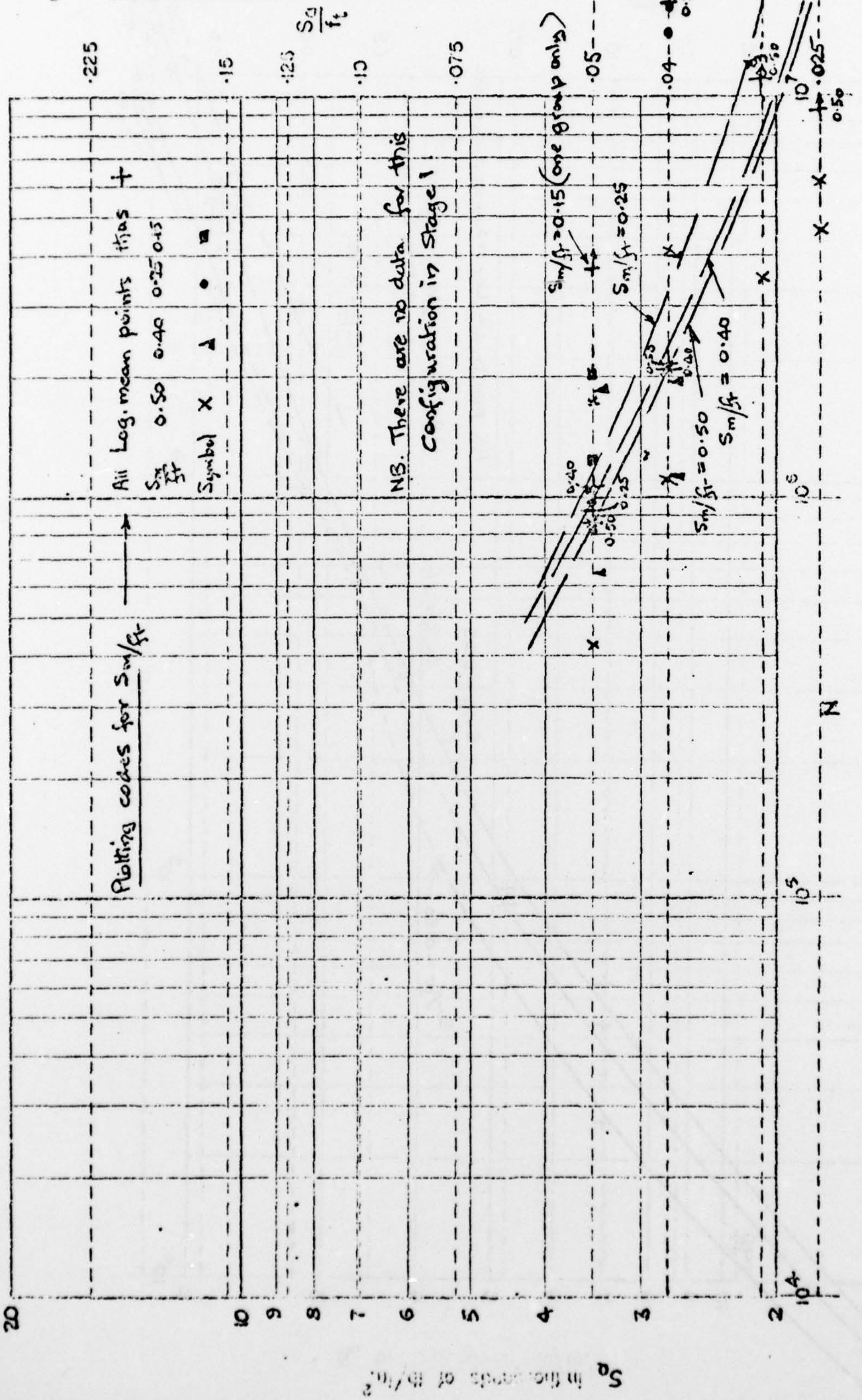


S1137 9 - LOW STRESS LEVEL TESTS   Ref TABLE 6

PUSH FIT PIN - PIN LOADED

FIG 6. MEDIUM SPECIMENS - TYPE 2D 15/32

$d/D = 3/8 \quad K_t' = 2.72$



S.L No 9 - LOW STRESS LEVEL TESTS.

PUSH FIT PIN - PIN LOADED

Ref: TABLE 7

FIG. 7 MEDIUM SPECIMENS - TYPE $2D\,5/8$ $d/D = 1/2$ $K'_t = 2.22$

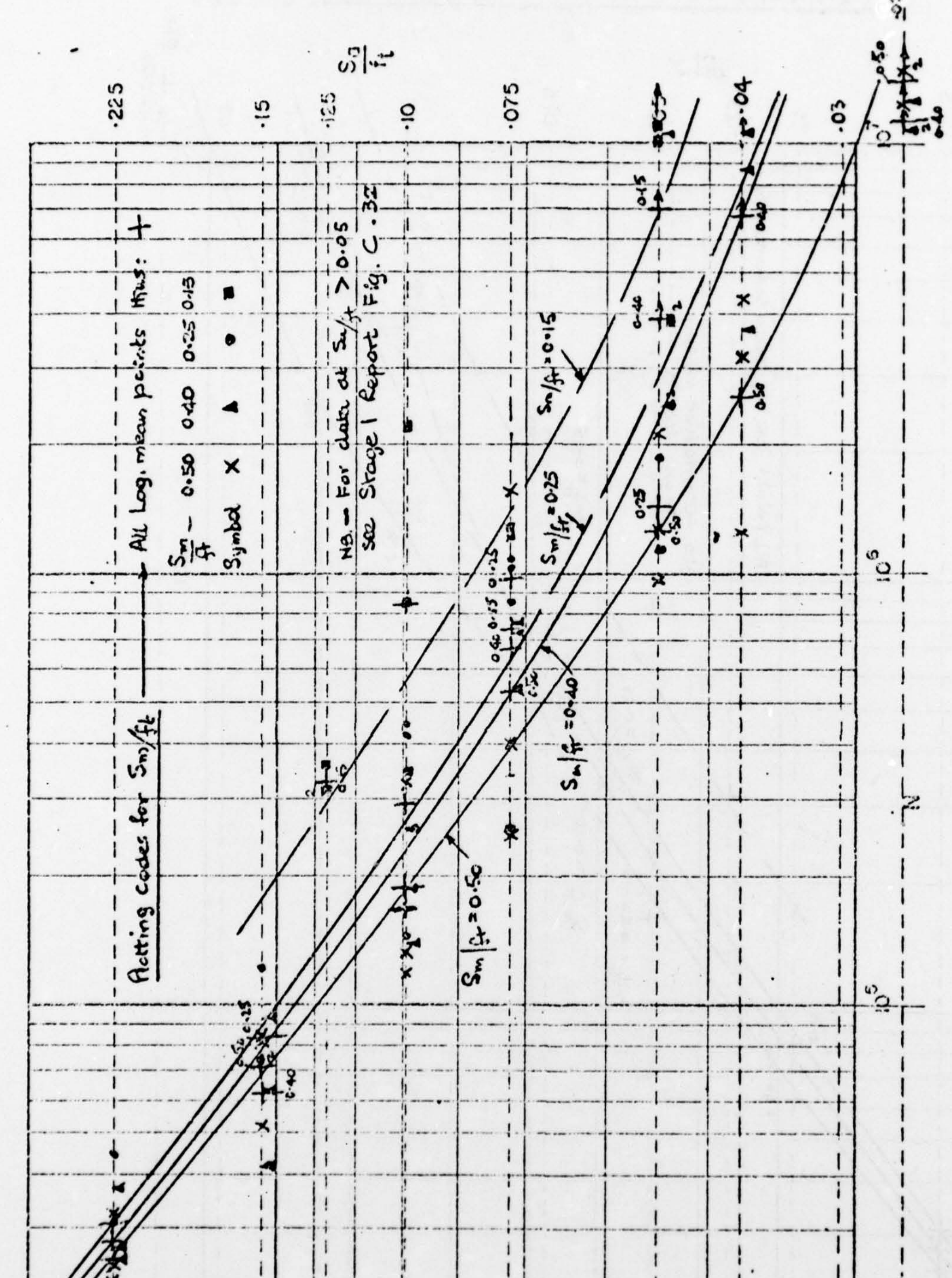
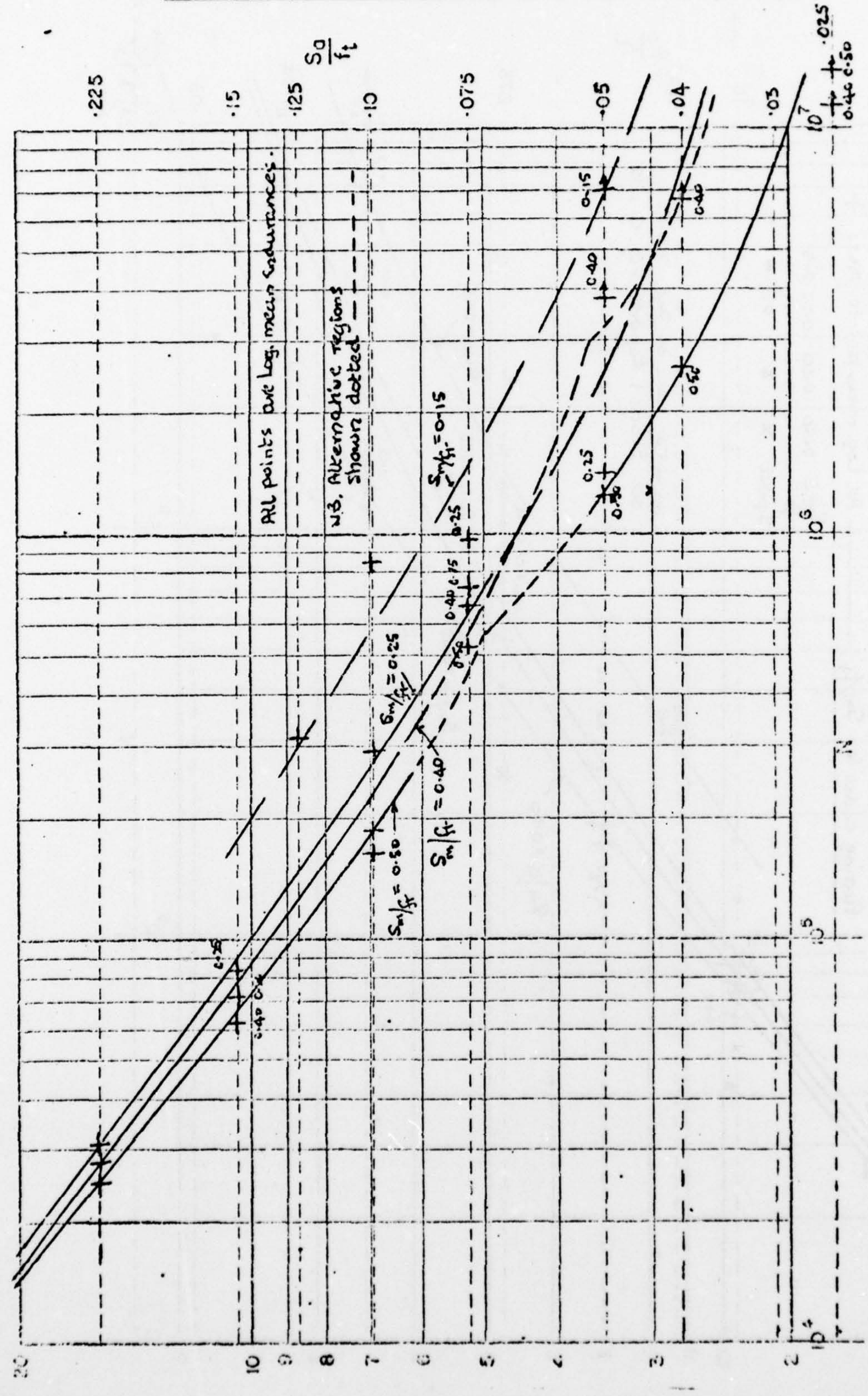


FIG. 7a - MEDIUM SPECIMENS - TYPE 2D 5/8 $d/D = 1/2$ $K'_t = 2.22$

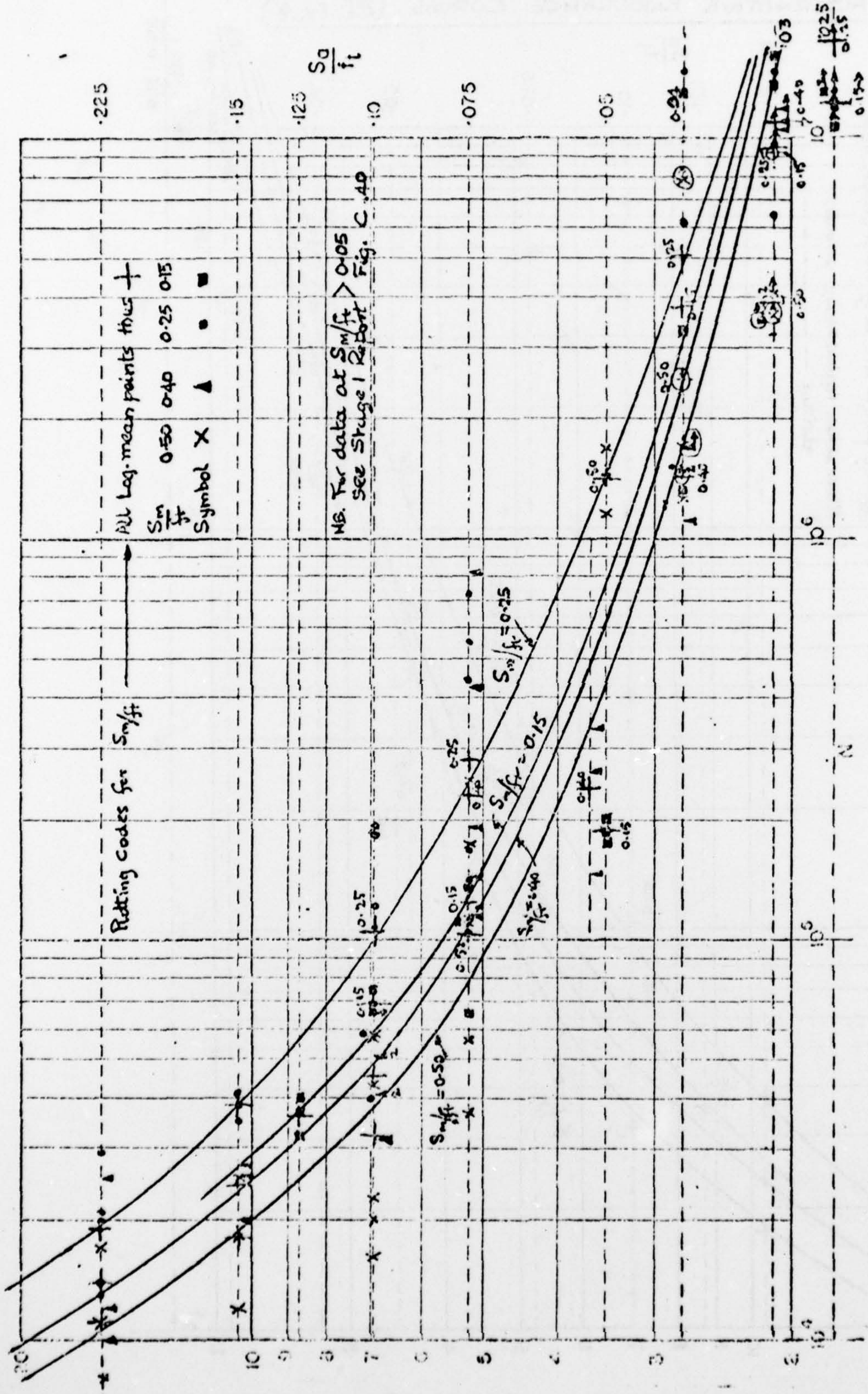
ALTERNATIVE ENDURANCE CURVES (c.f. Fig. 7)



S.I. No 9 – LOW STRESS LEVEL TESTS

PUSH FIT PIN – PIN LOADED   REF. TABLE 8

FIG. 8   SMALL SPECIMEN TYPE $4B_1\ 3/16$ $d/D = 1/4,\ K'_t = 3.73$

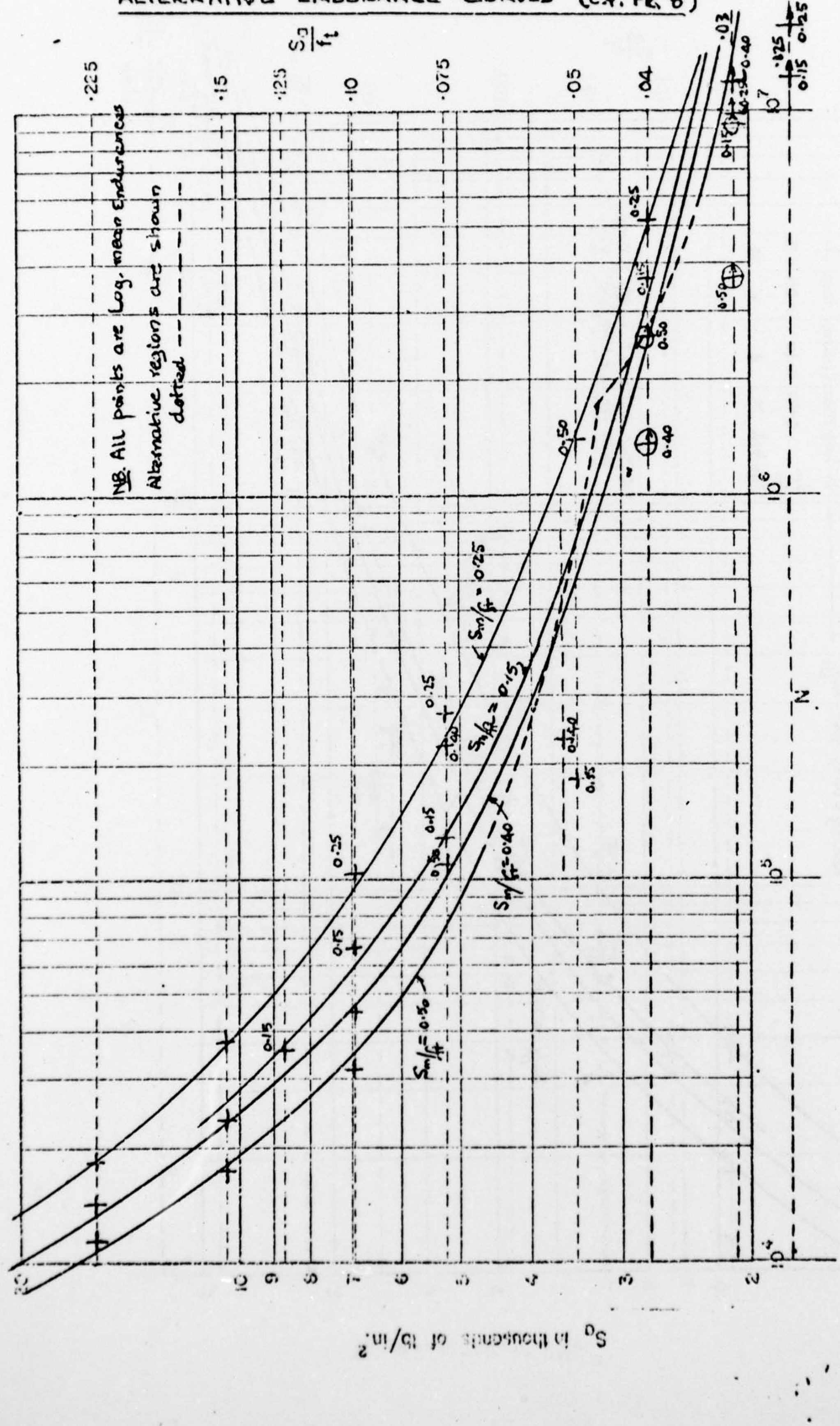


Sl. N° 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED

FIG. 8a SMALL SPECIMEN - TYPE 4B, 3/16 $d/D = 1/4$ $K'_t = 3.73$

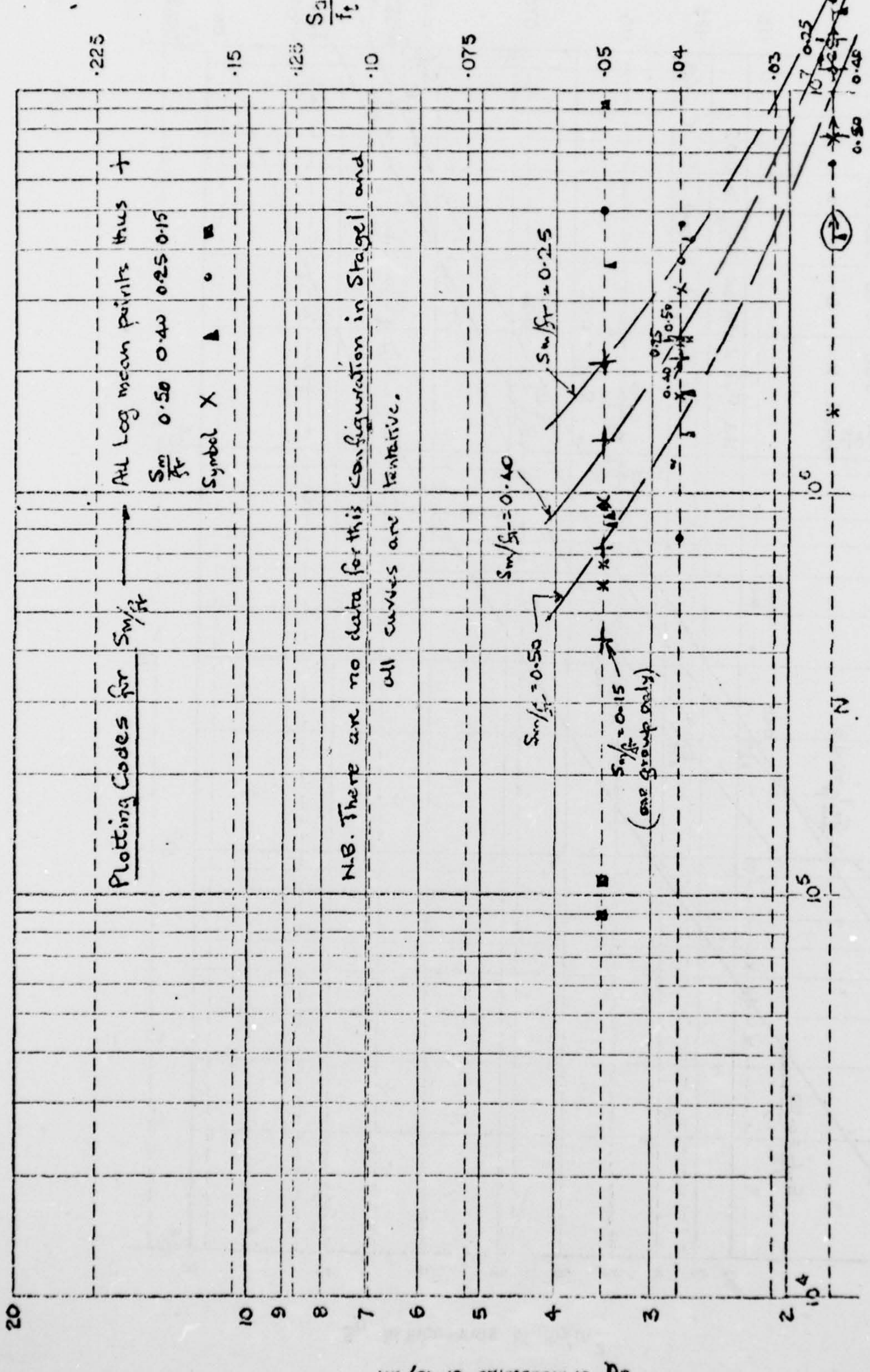
ALTERNATIVE ENDURANCE CURVES (c.f. FIG 8)



SI. No 9 - LOW STRESS LEVEL TESTS

PUSH FIT PIN - PIN LOADED   Ref. TABLE 9

FIG 9   SMALL SPECIMENS TYPE 4D 9/32 $d/D = 3/8$ $K_t' = 2.72$



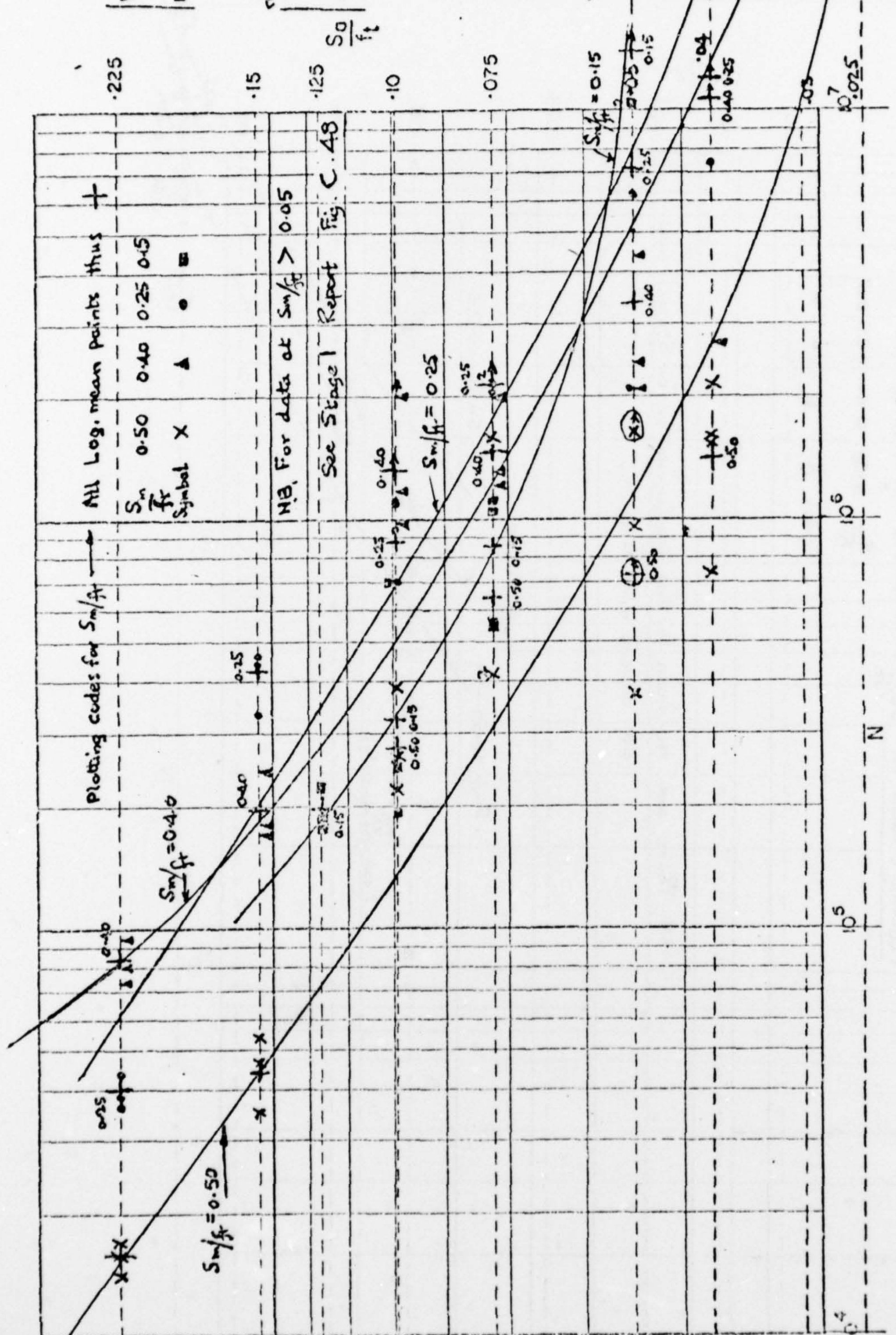
S.I. No 9 - LOW STRESS LEVEL TESTS

Ref. TABLE 10

PUSH FIT PIN - PIN LOADED

FIG 10 SMALL SPECIMEN - TYPE 4D 3/8

$d/D = 1/2$ - $K_t' = 2.22$



S1. No 9 — LOW STRESS LEVEL TESTS

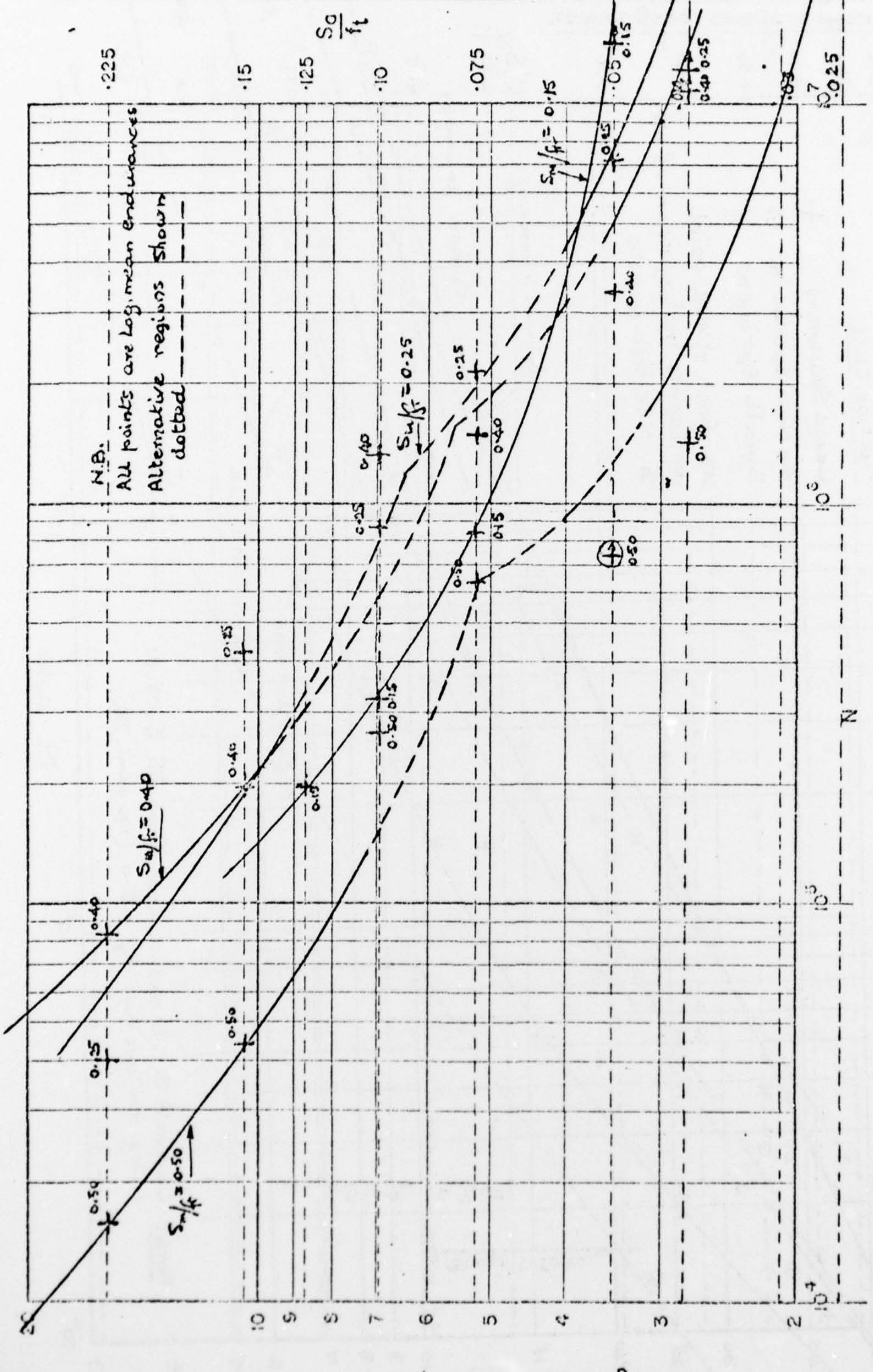
PUSH FIT PIN — PIN LOADED

FIG 10a SMALL SPECIMEN - TYPE 4D 3/8

$d/D = 1/2$

$K'_t = 2.22$

ALTERNATIVE ENDURANCE CURVES (cf. Fig 10)

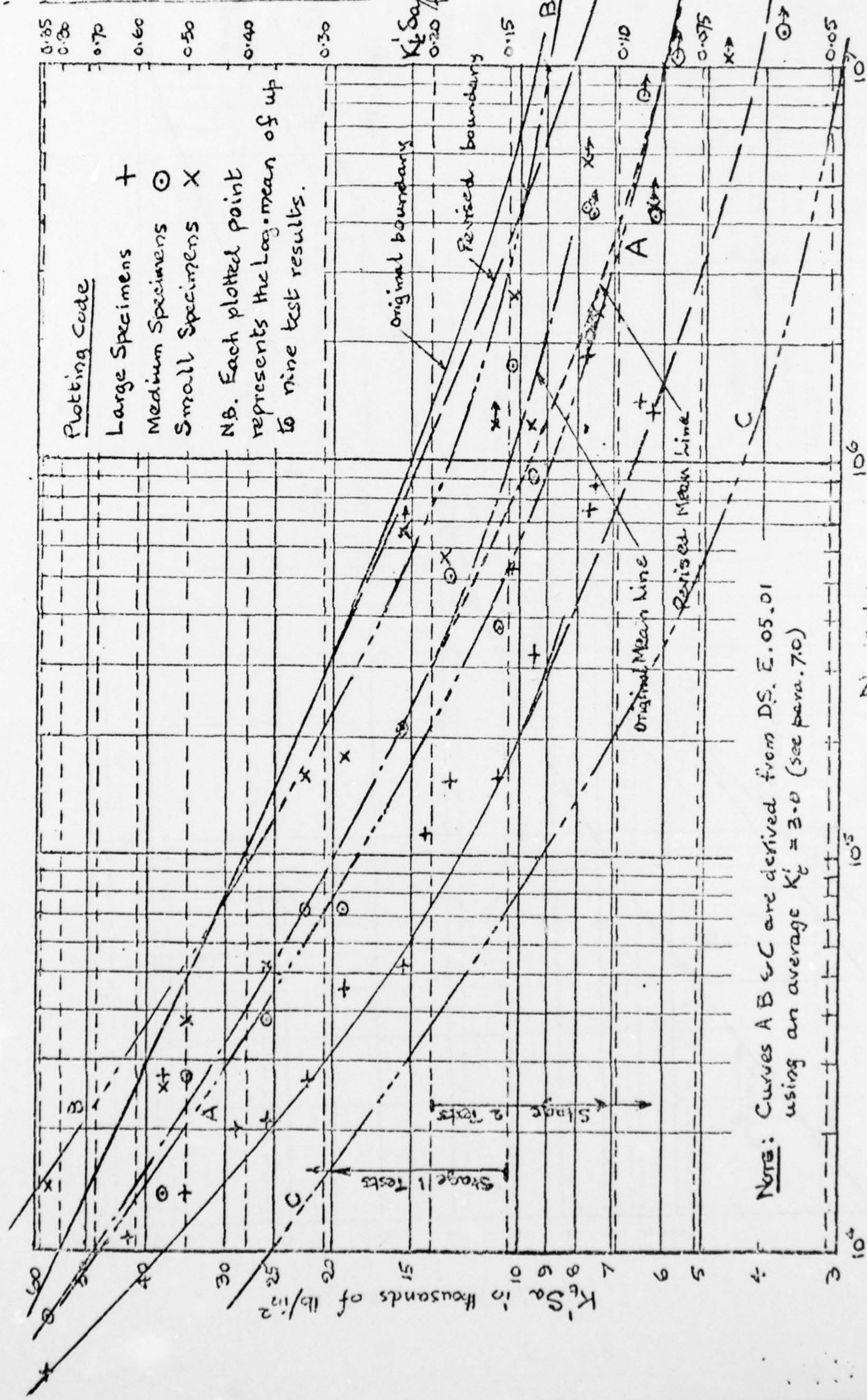


S.I. Nº 9 LOW STRESS LEVEL TESTS

PUSH FIT PIN – PIN LOADED (Ref TABLES 11a & 11b)

FIG. 11 SUMMARY PRESENTATION

COVERING ALL SIZES & VALUES OF d/D
& MEAN STRESSES 0.25fc & ABOVE.



REPORT DOCUMENTATION PAGE

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3134000R	ENGINEERING SCIENCES DATA UNIT, LONDON, UK

5a. Sponsoring Agency's Code (if known)	6a. Sponsoring Agency (Contract Authority) Name and Location
7248000N	PROCUREMENT EXEC., MIN. OF DEFENCE, DR AIR, UK

7. Title

BOLTED JOINT FATIGUE PROGRAMME, VOLUME 4, STAGE 2, SUPPLEMENTARY INVESTIGATIONS 7 TO 9

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers). Title, place and date of conference

8. Author 1, Surname, initials	9a Author 2	9b Authors 3, 4...	10. Date	pp	ref
Sandifer, R.H.			5.1978	150	3

11. Contract Number	12. Period	13. Project	14. Other References

15. Distribution statement

Descriptors (or keywords)

*Bolted joints, *Fatigue (materials), Aluminium alloys, Fatigue tests, Photoelasticity, Steels, Stress corrosion

Abstract The programme consisted of two major parts - a photoelastic investigation into the stress distribution and resulting stress concentration factors in a family of simple bolted joints, and a correlated series of fatigue tests on bolted metal joints having the same geometrical form as the photoelastic ones using a commonly employed aluminium alloy for the plates and a steel in current use for the pins.

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